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SATURN V/S-IVB STAGE MODIFICATIONS FOR PROPELLANT CONTROL DURING ORBITAL VENTING

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ERRATA SHEET

Page 9, Figure 1	The figure on the left is the Saturn V configuration; the figure on the right is the Saturn IB configuration.
Page 27, Figure 5	The horizontal line across the tank on the figures labeled Deflectors, Ring Baffles and Deflector, and Egg Crate and Deflector indicate fluid level. The middle line of the three horizontal lines of the figure labeled Egg Crate indicates fluid level.
Page 52, Figure 18	.032 wt whould read .032 thickness.
Page 53, Figure 19	In the upper left hand diagram, the plate shown just below the screen door is a solid deflecting plate, .032 thickness.
Page 95, Figure 24	The dashed horizontal lines shown in the diagram are there merely to indicate fluid.

PREFACE

In response to Change Order 502 to NAS7-101, dated March 17, 1965, Douglas Aircraft Company, Inc., has initiated an effort toward analysis, design, fabrication, test and installation of various components and systems associated with the S-IVB stage. More specifically, the work to be accomplished is directed toward insuring adequate propellant control during orbital coast so that liquid vented overboard is minimized. This report presents the work accomplished during a three-weeks preliminary design phase in which various stage modifications were evaluated. The results of these evaluations have led to the recommendations presented herein for structural changes to the stage as well as further detailed analysis. In addition, estimates of program schedule impact are presented.

ACKNOWLEDGEMENT

The information presented in this report reflects the coordinated effort of Advanced Saturn and Large Launch Systems directed by T. J. Gordon and Saturn Engineering, A. P. O'Neal, Chief Engineer. Technical effort was contributed by specialists in the various disciplines under the supervision of the following:

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1.0 INTRODUCTION AND SUMMARY

1.1 Introduction

The success of the Saturn program is highly dependent on the satisfactory performance of the S-IVB orbital vent system. Thus, strict control over venting must be maintained to insure adequate conditions for orbital restart of the stage.

Currently, there are many uncertainties in the understanding of low gravity fluid mechanics and heat transfer phenomena. Some of these uncertainties result from the fact that design data is obtained from extrapolation of the sparse experimental data as well as extending the correlation to gravity regimes as low as 2×10^{-5} g. Also, the results of the recent flight of Centaur AC4 caused significant concern and cast some doubt on the validity of the methods and correlations that have been used to design some of the present Saturn systems.

1.2 Summary

Recent flight data and subsequent analytical correlations have caused concern that the following problems may prove significant to the S-IVB stage during the orbital coast period of the lunar mission:

a. Slosh at cutoff due to boost disturbances
b. Feed line and recirculation return line disturbances (geysering due to fuel pump pressure decay at shutdown and excessive chilldown return velocities)
c. APS control cycling and propellant sloshing coupling effect (orbital slosh)
d. Liquid agitation caused by thermal circulation, bulkhead springback, etc.
e. Liquid venting and/or liquid entrainment as a result of the above four items.

In response to an MSFC request to determine and recommend means of controlling propellant behavior, including hardware implementation, the following studies and/or design change recommendations are made:

a. A 22-inch slosh baffle is being installed in the LH_2 tank to decrease slosh amplitudes at boost cutoff.

b. The burn time of the 70-pound Gemini engines (used for propellant settling after MECO) is being extended from 50 to 91 seconds to minimize shutdown boost slosh amplification.

c. A liquid deflector is being placed in the ullage to aid in deflecting the slosh wave at boost termination and the orbital slosh that exists due to APS control cycling.

d. A simple static device is being placed in the ullage to aid in minimizing propellant loss due to entrainment.

e. Diffusers are being incorporated over the recirculation return lines and propellant feed duct exits in both propellant tanks to eliminate the possibility of geysering at MECO and excessive chilldown return velocities.

The total stage weight penalty associated with these changes is estimated to be 156.7 pounds for S-IVB/203 and 149.3 pounds for S-IVB/Saturn V.* This report presents the detailed technical studies, considerations, concepts, design layouts, and final recommendations of the mentioned systems that DAC believes are feasible for implementation to the S-IVB stage to aid in insuring the success of the orbital vent system.

In addition, studies are continuing to determine the feasibility of changing the control logic of the Coast Attitude Control System to reduce orbital slosh excitation. If deemed feasible, the need for ullage baffle and possibly the liquid/vapor separator may be eliminated.

The present layouts show a liquid deflector with a 12-foot opening in the center of the tank. This would seriously impair the TV viewing angle. It has been proposed that the deflector be scalloped out to insure adequate TV coverage. However, it must also be determined if the baffle will seriously impair lighting attenuation. If it is found to be a problem then a compromise solution will have to be established, i.e., more intense lighting,

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* See Appendix C for detailed weight estimate breakdown.

higher placement of the deflector, or a shorter deflector. A decision must first be made regarding the relative importance of TV coverage or minimization of the amount of liquid reaching the vent.

Conceptual designs of several backup orbital vent systems which DAC believes are feasible for 504 incorporations are also presented. These concepts will be further discussed on May 1, at which time DAC will make specific recommendations for the system deemed most feasible. Basically, the concepts that appear feasible are in the following categories:

a. Cyclic venting
b. Orientation of LH_2 using screens
c. Rolling the vehicle to act as a centrifuge and cyclic venting.

Since the proposed modifications entail out-of-position installation, some schedule slippage is anticipated. The estimated program impact is a 20-day schedule slippage on S-IVB/203 decreasing on subsequent stages until S-IVB/504 which is caught in position with no slippage.

Douglas is evaluating the work to be accomplished at STC to see if this effort can be accomplished in parallel with other tasks on a non-schedule interference basis. The schedule shown herein depicts the impact on affected vehicles if this installation is accomplished at the Space Systems Center.

2.0 S-IVB TECHNICAL APPROACH

S-IVB Venting System Description and Operational Sequence

In order to understand the problems and the need for the proposed solutions, a cursory description of the S-IVB operating conditions related to possible low gravity and shutdown phenomena will be discussed.

The S-IVB stage for Saturn V must burn to achieve initial orbit, coast in orbit up to 4.5 hours while maintaining strict attitude control limits, restart, and burn to a lunar trajectory. At first burn MECO, two axially directed 70-pound thrust engines located in the Auxiliary Propulsion System (APS) modules burn for 50 seconds to insure that the liquid propellants are settled before the continuous venting is initiated.

Near the end of the 50-second ullage engine burn period, continuous venting is initiated and continues until engine restart. The thrust from the continuous vent system (CVS) is directed axially to provide approximately 2×10^{-5} g forward acceleration to keep the propellants settled. This approach will assure that the liquid will be settled for engine restart and will result in a reduction in liquid hydrogen and oxygen boiloff. Relief venting (if required) is accomplished through a non-propulsive system using large diameter ducts. The successful operation of the orbital vent system under low gravity conditions is of critical importance to the success of the overall S-IVB and Apollo missions.

Technical Considerations

Potential Problem Areas

Recent flight data and analyses indicate the possibility of problems occurring in the following areas:

a. Propellant slosh wave height that occurs during S-IVB boost tends to amplify enormously (factor of 40 for Saturn V) upon termination of main engine thrust. This could cause liquid to slosh up to the vent region, thus increasing the possibility of liquid venting. Coupling the boost slosh amplification with the shutdown transient phenomena indicates the possibility of violent surface agitation. The transient phenomena under consideration are bulkhead springback and conversion of the kinetic energy that exists in both the boundary layer (due to convection heat transfer) and main propellant bulk (due to the draining velocity) to potential energy.

b. Closing of the main engine valves at MECO can result in large pressure spikes in the LOX and LH_2 feed ducts due to the pressure decay on the high pressure side of the main propellant pumps as well as water-hammer effects. The forces could result in high velocity liquid surges expelling into the main tanks via the feed ducts and chilldown system return lines. Since the damping forces in hydrogen are very low, surges of any appreciable velocity could result in a geysering stream of LH_2 directed forward which could easily break through the liquid surface and possibly reach the forward dome and be vented overboard.

c. The attitude control system will induce propellant sloshing during orbital coast. The limit cycle pulse rates of the APS system may be very close to the natural frequency of liquid hydrogen sloshing, thus, causing a coupling effect with resulting slosh waves that could conceivably reach the forward dome and vent area. This, of course, could cause liquid venting and/or entrainment which could seriously impair mission success if the quantity of liquid vented was significant.

The solution to these problems is not simple in that certain ground rules must be adhered to. The most pertinent factor to be considered was that of scheduling. In order to meet the present flight schedules, it is necessary that system changes be as simple as possible, yet sufficient to provide an ample solution. Therefore, in general, major system redesigns are not possible. The remaining sections of this report outline the various changes that were considered as solutions. These items are discussed in considerable detail with layouts provided for the recommended solutions.

Studies are continuing in three areas and results of these studies may significantly affect the systems designs to date. The first of these studies is to determine the cross coupling effects between the Coast Attitude Control System propellant sloshing. Preliminary results indicate that a potential problem does exist as a result of the coupling effect, and therefore, the deflector has been placed in the ullage and a standpipe which acts as a simple separator installed. These items could conceivably be eliminated in the future if studies show that the problem can be solved by changing the control logic of the Coast Attitude Control System to minimize the amount of sloshing excited during coast.

The second study that is continuing is that of investigating the need for additional control of LOX motion at shutdown. This could possibly mean installing an additional baffle. Only the S-IVB/V series of vehicles will be affected by this study as the 203 experiment is programmed for LOX depletion at MECO. It is assumed that no problems will be caused by motion of any residual LOX.

Numerous orbital backup systems were evaluated for possible use on the Saturn V series should the present continuous venting concept prove inadequate. The prime consideration was again that of scheduling. The chosen backup system must be available for vehicle 504 and should be a "kit" type package. Thus, these ground rules eliminated a large number of proposed concepts. By May 1, DAC will have completed studies on the backup system and make more specific recommendations than the cursory results shown here.

Performance Trade Factors

For the S-IVB/V vehicle, the solution to the problem of increased venting of LH_2 requires consideration of the addition of a fuel reserve to supplant the vented LH_2. This must be considered as an alternate to increased structural weight caused by placement of baffles and other apparatus in the tank. Regarding the latter approach, the payload penalty is equivalent to the structural weight added to the stage. The former approach, additional LH_2 of offset venting losses, causes a payload degradation of 0.41 pounds per pound of additional hydrogen vented. Consequently, for the Saturn V/LOR mission, additional structure will provide better performance whenever the increase in structural weight is less than 41 percent of the weight of vented propellant saved by the structural additions. The present potential for additional LH_2 reserve is estimated to be 1,000 pounds.

The trade factor associated with the 203 LH_2 orbital experiment need not be considered with regards to selection of the design solution, but is of interest with regards to planning the experiment. The following trade factors are applicable to the 203 experiment: (1) A decrease of 3.8 inches in LH_2 cutoff level per 1,000 pounds of additional structural weight. (2) A reduction of 0.5 pound of LH_2 at cutoff per 1 pound of additional S-IVB structural weight.

2.1 Slosh Baffles

Propellant sloshing dynamics are included in analyses to determine vehicle flight control system and attitude control system stability and response characteristics. For these analyses, the phenomena on which is considered is the forces exerted on the vehicle by the sloshing propellant. When venting of tank ullage gasses is required, the location and motion of the propellant during sloshing must also be considered in establishing tank vent system design criteria. The effect of sloshing motion on the quantity of propellant boiloff because of increased heat transfer from the walls to the liquid must be included in these criteria.

If propellant motion causes liquid to reach the vent inlet and to be vented, or causes increased boiloff, two adverse effects will result. First, loss of propellant will decrease vehicle performance and result in a degradation of payload capability. Second, the increased flow rate out of the vent will increase the thrust applied to the vehicle by the vented propellants. This will result in increased disturbing moments being applied to the vehicle. Disturbing moments can be increased even though, as is the case with the S-IVB, the vent system utilizes two vents which are located symmetrically on the vehicle so that they ideally induce no disturbing moments. This is because manufacturing tolerances will introduce thrust magnitude and alignment variations.

Although both of these effects have an adverse effect on the vehicle, additional venting is not necessarily unacceptable. The performance penalty resulting from the loss of propellant directly by venting or indirectly by increased boiloff may be tolerable, or may be less than that resulting from the weight of design changes to prevent or reduce the loss of propellant. If the attitude control system has adequate control capability, the additional disturbing moments resulting from venting of liquid or increased venting of gas will not cause loss of control, but will increase attitude control propellant usage. The increased attitude control propellant usage may, however, be a negligibly small quantity.

If increased venting is shown to be unacceptable, two approaches to preventing, or at least minimizing, the venting of liquid are possible. The vent system can include a liquid/vapor separator, as was previously included in the S-IVB, which is designed to eliminate or minimize the venting of liquid, or the propellant motion can be controlled by the addition of slosh baffles or by control system design to minimize propellant slosh motion.

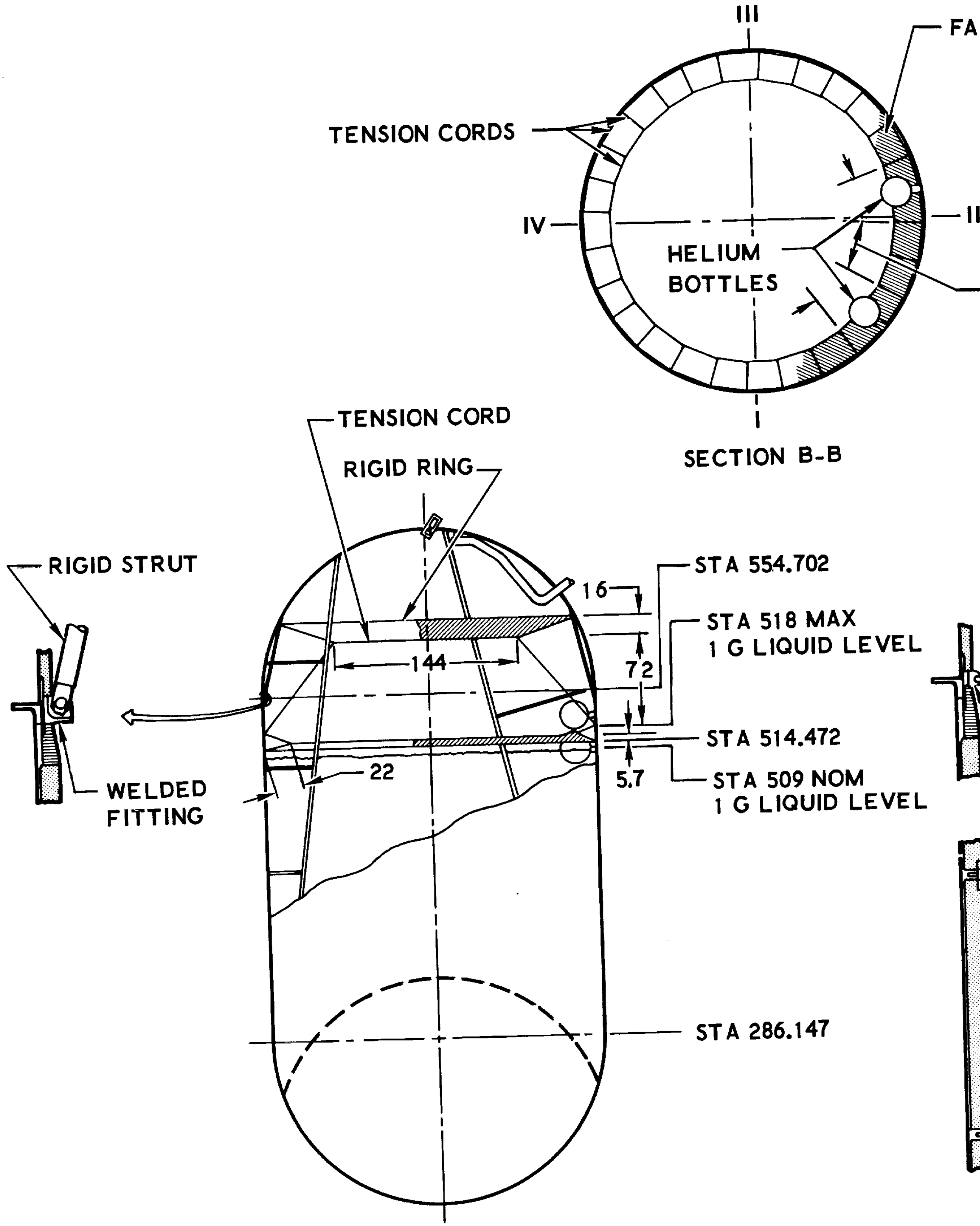
This section will discuss the results of studies to date to identify those phenomena which contribute to propellant sloshing motion during earth orbit and to determine the magnitude of the induced sloshing. Possible designs of baffles or other devices to maintain this motion within acceptable limits are also discussed.

The immediate action proposed to solve the potential cutoff slosh problem is to install a ring baffle and a deflector in the hydrogen tank and to extend the burn time of the APS engines from 50 to 91 seconds. The baffle will be located in the vicinity of the liquid level and the deflector near the junction of the LH_2 cylinder and forward dome.

The size and position of the baffle and deflector has been determined based on bubble entrapment considerations. The degree of propellant sloshing control provided by this baffle and deflector will be determined.

A preliminary design layout showing the proposed baffles and their orientation within the S-IVB LH_2 tanks is shown in Figure 1.

The baffle and the deflector are shaped as frustrums of cones with the bases attached to the tank wall. With the exception of part of the Saturn V deflector, they are made of fabric supported by tension cords to take slosh



III
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IV
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TENSION CORD
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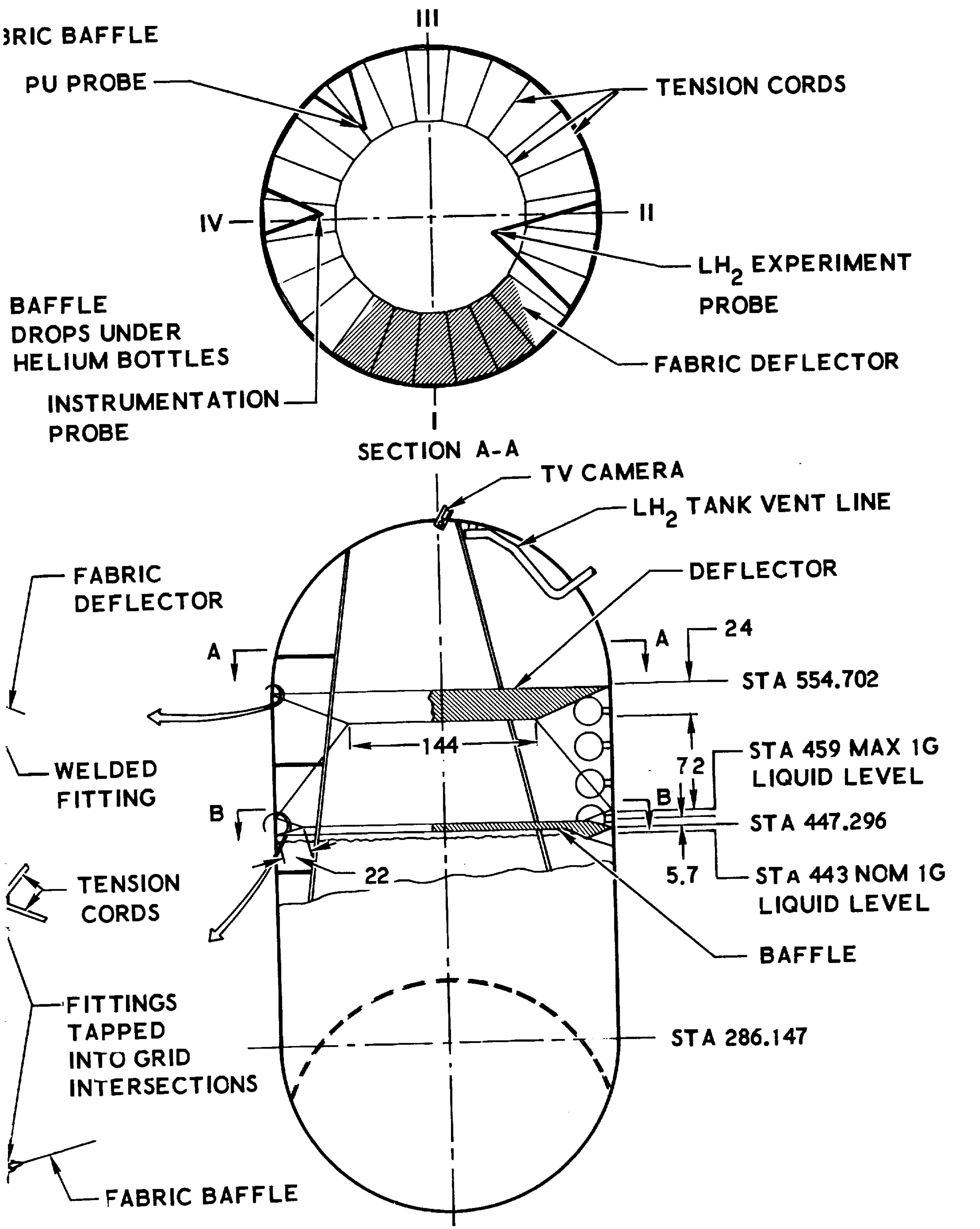


FIGURE 1 PROPOSED LH_2 TANK BAFFLES

loads to the tank wall. The Saturn V deflector is supported at its upper end by rigid tubing since the forward dome is not capable of taking loads at this point.

Slosh loads are estimated to be approximately 0.1 psi. For this low loading, fabric is feasible for baffling and offers several advantages over rigid materials. It is lighter than rigid baffles, it has the ability to expand and contract with the tank, and is much easier to install on a completed vehicle where all parts must be fed through the access door in the forward dome. A limited amount of testing has been done on fabrics and cords in liquid hydrogen and more tests are being run currently. Preliminary results show nylon fabric and cords to be suitable.

Attachment to the tank wall is made in two ways. The forward attachments are fittings welded to the tank skin at the dome to cylinder intersection. On Vehicle 203 insulation must be removed locally for each of the fittings and then replaced after welding. The aft attachments to the tank fall in the cylindrical section which is of waffle grid construction. In this area eyebolt type fittings are threaded into tapped holes at the grid intersections. Bolting through the tank wall as is done in the LOX tank has been investigated as an alternate to both of the above methods. This would eliminate welding which is difficult in an insulated tank, and would eliminate threaded holes in the aluminum tank skin. Preliminary leakage tests using helium gas in a liquid hydrogen environment are encouraging, however more sophisticated testing must be done to prove the reliability of this method of attachment before using it in the LH_2 tank. This testing has been initiated and will commence when the special fasteners arrive from the manufacturer.

2.1.1 Design Considerations

The baffle design must consider both physical phenomena and structural or operational interference with other internal systems. By its very nature, a baffle provides blockage to flow, be it liquid or gas. If a ring baffle is located in the ullage, gas velocity through the remaining open area is increased with a corresponding increase in entrainment. Also, any liquid projected above the baffle experiences difficulty in returning to the bulk. If a solid baffle is located below the liquid level, bubbles due to boiloff are subject to entrapment increasing the possibility of excessive liquid level rise.

Ullage baffles will interfere to some extent with the 203 LH_2 experiment TV coverage through both field of view blockage and light intensity reduction. Tank instrumentation including PU probes must not be seriously compromised. The following paragraphs explore the merits of several types of baffles.

Propellant sloshing during orbital coast can be excited by several methods. These include persistence of sloshing existing during boost, amplification of slosh when thrust acceleration is reduced at boost termination, and coupling between the propellant dynamics and the coast attitude control system. In the following sections, each of these phenomena will be discussed and the magnitude of resulting sloshing determined. Possible methods of minimizing the resulting sloshing will also be discussed.

2.1.1.1 Boost Slosh

Sloshing during S-IVB boost can be caused by two principal types of excitations. The first type are excitations which occur only once early in flight. These include separation disturbances, guidance initiation disturbances and sloshing which is present in the S-IVB prior to separation from the lower stage. The second type are continual excitations such as are caused by limit cycling of the attitude control system. The sloshing caused by initial conditions, separation disturbances and guidance initiation disturbances will decrease in magnitude during boost because of the damping inherent in the propellant tanks, and can be damped more if necessary by the addition of baffles. The sloshing caused by attitude control system limit cycling will vary throughout boost as the vehicle dynamics cause changes in the amplitude and frequency of the vehicle limit cycle. The sloshing magnitude will tend to be increased when the limit cycle amplitude increases or when the limit cycle frequency approaches the natural frequency of a sloshing mode. The sloshing present during boost can consist not only of first mode, but also of second and higher modes. These higher modes can be excited by all of the factors discussed previously. The magnitude of the resulting second and higher mode slosh will depend on the frequency characteristics of the slosh exciting disturbances. The low damping ratio which is typical of propellant sloshing will preclude reaching steady state conditions so that a time varying parameter solution is required to determine sloshing amplitudes caused by limit cycling.

A preliminary evaluation of these slosh disturbances and methods of reducing them has been conducted with emphasis in the following areas:

a. Saturn S-IV flight test data which indicates sloshing and vehicle limit cycling

b. Lower stage and separation originated slosh

c. Limit cycle induced slosh.

These evaluations are discussed in the following sections.

2.1.1.1.1 S-IV Flight Experience

Sloshing information has been obtained from all S-IV flight tests to date. The information on S-IV-5 and S-IV-6 has been documented in the Flight Evaluation Reports SM-46018 Vol. II and SM-46054 Vol. II, respectively. Sloshing heights are obtained through the propellant utilization mass sensors and are transmitted as propellant mass changes. Since there is only one sensor in each tank, the maximum slosh height is recorded only when it is the plane of the sensor. The slosh heights recorded for all S-IV flights are shown in Figure 2. The slosh heights shown in this figure are half amplitudes based on maximum peak-to-peak oscillations, and thus are the sum of all sloshing modes. This figure shows that the maximum LH_2 slosh amplitude was 3-1/2 inches. This peak amplitude occurred early in S-IV flight, and was thus caused by stage separation and guidance initiation transients and by residual sloshing from lower stages. All amplitudes used here are zero to peak values as defined by A in the Equation $h_s = A \sin wt$. This sloshing decayed slowly during flight in all cases. The decay of sloshing amplitude shown in Figure 1 indicates that an effective damping ratio of 0.0015 existed in the LH_2 tank. The slosh heights for these vehicles at 30 percent burntime had decreased to between 2 and 2-1/4 inches amplitude. This burntime corresponds approximately to the burntime prior to earth orbit injection for S-IVB/V. Use of these data for design of S-IVB/SAT V would yield a slosh amplitude at orbit injection of 2-1/4 inches. However, because of the one sensor configuration mentioned above, these may not be the maximum S-IV slosh heights. In addition, these data alone do not fully establish the S-IVB slosh heights.

Unlike slosh heights, frequencies can be determined rather accurately as they do not depend on sensor location. Frequency comparison on S-IV-6 indicates that LH_2 was excited by first mode LOX sloshing. This interaction suggests that both propellants must be considered when evaluating or predicting LH_2 slosh disturbances. Although LOX sloshing can effect LH_2 slosh heights, the inverse effect is considered negligible since the density of LH_2 is very small and its slosh forces have little effect on the vehicle.

Accelerometer and engine position data on S-IV-5 indicated that a limit cycle condition existed primarily during the latter half of flight. Limit cycling, a stable but oscillatory vehicle movement, can easily excite sloshing if limit cycle frequencies are very near the slosh resonant frequencies as is the case on the S-IV and S-IVB vehicles. Limit cycling is caused by control system non-linearities such as actuator hysteresis and gimbal friction. Gimbal friction is greater on the S-IVB than on the S-IV, therefore, slosh disturbances from limit cycling are expected to be larger.

2.1.1.1.2 <u>Lower Stage and Separation Originated Slosh</u>

As stated previously, maximum slosh heights at the mass sensor were 3-1/2 inches on S-IV vehicles. Separation studies on the basic Saturn IB/S-IVB vehicle have been conducted, and slosh heights of 12 inches are indicated for very conservative separation conditions. These conditions at the beginning of separation are 1 degree attitude error, 1 degree/second attitude rate error, 4 degree angle of attack and an initial dynamic pressure of 65 Kg/m^2. These initial conditions are greater than S-IV-5 for which an attitude excursion of 0.5 degree and an attitude rate of 0.3 degree per second was experienced at the beginning of separation. Although separation

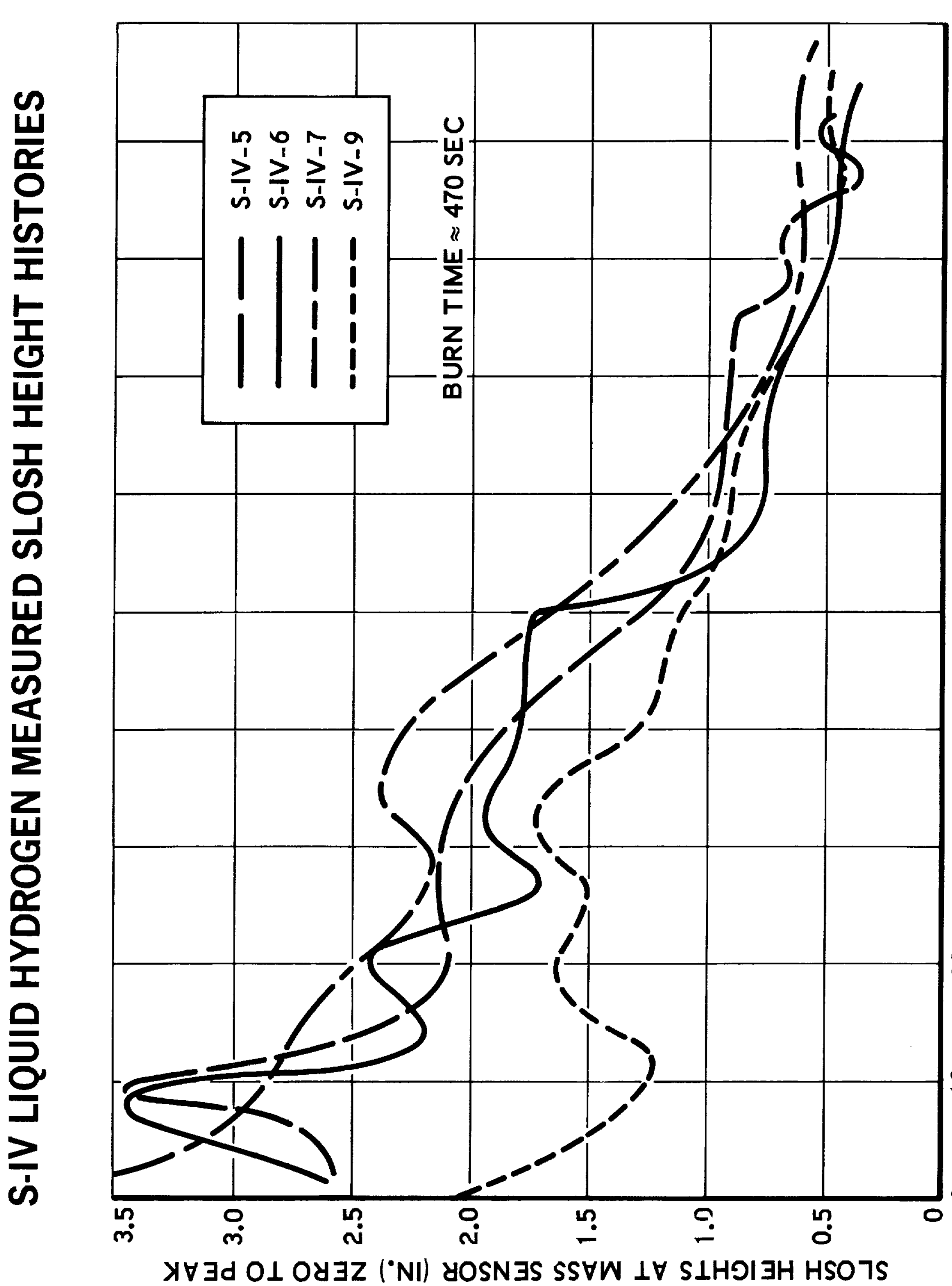

S-IV LIQUID HYDROGEN MEASURED SLOSH HEIGHT HISTORIES
S-IV-5
S-IV-6
S-IV-7
S-IV-9
BURN TIME ≈ 470 SEC
SLOSH HEIGHTS AT MASS SENSOR (IN.) ZERO TO PEAK
PERCENT BURN TIME
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
10
20
30
40
50
60
70
80
90
100

FIGURE 2

induced slosh amplitudes have not been determined for the Saturn V/S-IVB, these amplitudes are expected to be less than for the Saturn IB/S-IVB; however, sloshing present at S-II stage cutoff is not known. The addition of a baffle to S-IVB/V will decrease initial slosh amplitudes.

Based on the considerations stated above, the results of Saturn IB/S-IVB analyses and an extrapolation to S-IVB of S-IV flight test data, an initial slosh amplitude of 6 inches, zero to peak, has been used to determine baffle design criteria. This value is approximately twice that experienced on S-IV.

2.1.1.1.3 Limit Cycle Excited Slosh

Control system limit cycling is considered to be one of the principal causes of slosh on the S-IVB stage in addition to separation conditions. Analog simulations for Saturn IB/S-IVB have indicated that limit cycling will cause a first mode LH_2 slosh amplitude at the wall of 3 inches. This is in addition to the initial excitation at separation previously discussed. These values are not directly applicable to the Saturn V/S-IVB but are considered usable for design purposes.

The slosh damping required to diminish limit cycle induced slosh has been calculated and found to be relatively large. Steady state analyses based on a second order linear system indicates that baffles providing 50 percent of more damping are required to provide significant slosh attenuation due to limit cycling. Control system limit cycling provides a continual excitation to slosh. This excitation is continual but time varying. Therefore, a steady state solution provides only approximate results. The limit cycle frequency, although variable, is confined to a frequency region just above the sloshing resonant frequency. In this region, extremely large damping ratios are required to provide appreciable slosh attenuation. If the limit cycle frequency does correspond to the slosh natural frequency, baffles are effective.

2.1.1.2 Amplification of Boost Slosh at Cutoff

The sloshing which exists in the propellant tanks at the end of boost can be amplified by the acceleration change associated with main engine shutdown.

This effect can be explained by noting that a propellant sloshing mode can be represented dynamically by a second order mass-spring-damper system, in which the slosh mass is a function of tank geometry and the natural frequency is proportional to the square root of the acceleration field acting on the tank. For a boost vehicle in flight, the spring constant which provides the restoring force is thus proportional to the net thrust acceleration of the vehicle.

Consider the case in which the slosh mass is oscillating sinusoidally at boost termination, and at the instant of engine cutoff is in the undeflected position, thus having maximum velocity. Because of the reduction of the spring constant which results from the reduction in vehicle acceleration, the peak deflection, which is the deflection for which the potential energy of the spring is equal to the kinetic energy of the mass in the undeflected position, will be greater after shut down than before. Expressed mathematically, the slosh mass amplitude during boost is

$$A_B = A_{M_B} \sin \omega_B t \tag{1}$$

and the velocity of the mass is

$$\dot{A}_B = A_{M_B} \omega_B \cos \omega_B t$$

The slosh mass amplitude during ullage thrusting after boost termination is

$$A_u = A_{m_u} \sin \omega_u t \tag{2}$$

and the velocity is

$$\dot{A}_u = A_{m_u} \omega_u \cos \omega_u t \tag{3}$$

where ω is the sloshing natural frequency, t is time, and the subscripts u and B refer to ullage and boost respectively.

If at cutoff, the slosh mass displacement

$$A_B = 0 \tag{4}$$

and the velocity is

$$A_B = A_{M_B} \omega_B \tag{5}$$

Conservation of momentum requires that after cutoff

$$\dot{A}_u = \dot{A}_B \tag{6}$$

from which it follows that

$$A_{m_u} = A_{M_B} \frac{\omega_B}{\omega_u} \tag{7}$$

Since the slosh frequency (ω) is proportional to the square root of the acceleration,

$$A_{m_u} = A_{m_B} \sqrt{\frac{a_B}{a_u}} \tag{8}$$

or

$$A_{m_u} = A_{m_B} \sqrt{\frac{T_B - D}{T_u - D}} \tag{9}$$

where T and D are the thrust and drag respectively.

Sloshing amplitude can thus be amplified by thrust reductions such as occur at boost termination.

For the case in which the slosh mass is at its maximum deflection with zero velocity when thrust is decreased, no amplification of slosh amplitude will occur. The reduction in thrust will cause a reduction in the spring constant of the slosh model and the change in slosh frequency noted above, but the slosh amplitude after boost cutoff will not be increased.

It can be shown that the ratio of the maximum slosh amplitude after an acceleration change can be calculated by

$$R = \frac{A_2}{A_1} = \sqrt{\sin^2 \omega_1 t + \left(\frac{a_1}{a_2}\right) \cos^2 \omega_1 t} \tag{10}$$

where ω is the slosh natural frequency and t is the phase of the slosh displacement. This equation has a maximum value for $= 0, \pi, 2\pi, \cdots$ and a minimum for $t = \frac{\pi}{2}, 3\frac{\pi}{2}, \frac{5\pi}{2}$, etc.

For the S-IVB, which experiences an additional thrust reduction from ullage thrust to continuous venting thrust, a second magnification of slosh amplitude can occur. The fact that the amount of sloshing magnification, given by Equation 10 is a function of the time at which cutoff occurs, suggests timing of boost termination to minimize slosh amplification. Although guidance and sensing considerations make timing of boost termination to reduce slosh disturbances during ullage impractical, another similar approach is practical. The total amplification of boost slosh in going from boost to ullage to continuous vent thrust is the product of the amplifications occurring at boost termination and at ullage thrust termination. Equation 10 shows that each of these amplifications can vary between 1 and a_1/a_2 depending on the phase of the sloshing oscillation at thrust termination. The maximum total amplification occurs when the first thrust termination coincides with a maximum kinetic energy condition of the slosh wave. If for this condition, the second thrust termination can be timed to coincide with a maximum potential (minimum kinetic) energy of the slosh wave, total amplification will be minimized. This requires that the ullage duration be equal to $t_u = (2n - 1)\pi/2$ or, since $\omega = 2\pi f = \frac{2\pi}{T}$, where f = slosh (11) frequency and $T = \frac{1}{f}$, $t_u = \frac{2n-1}{4} T$, that is, the ullage time should be equal to any odd number of quarter slosh periods. The LH_2 slosh period for the S-IVB/V during ullage thrusting (140 lb. total) is 121 seconds, thus either 30.3 or 91 seconds of ullage time should be used. The basic propellant settling requirements as presently known are a minimum of 50 seconds ullage time. Therefore, ullage time should be extended to 91 seconds.

The effect of ullage thrust duration on peak sloshing amplitude for S-IVB/V is shown graphically in Figure 3. This figure shows the peak LH_2 slosh

PEAK DISPLACEMENT OF LH_2 DURING FIRST COAST (SATURN S-IV B/V)

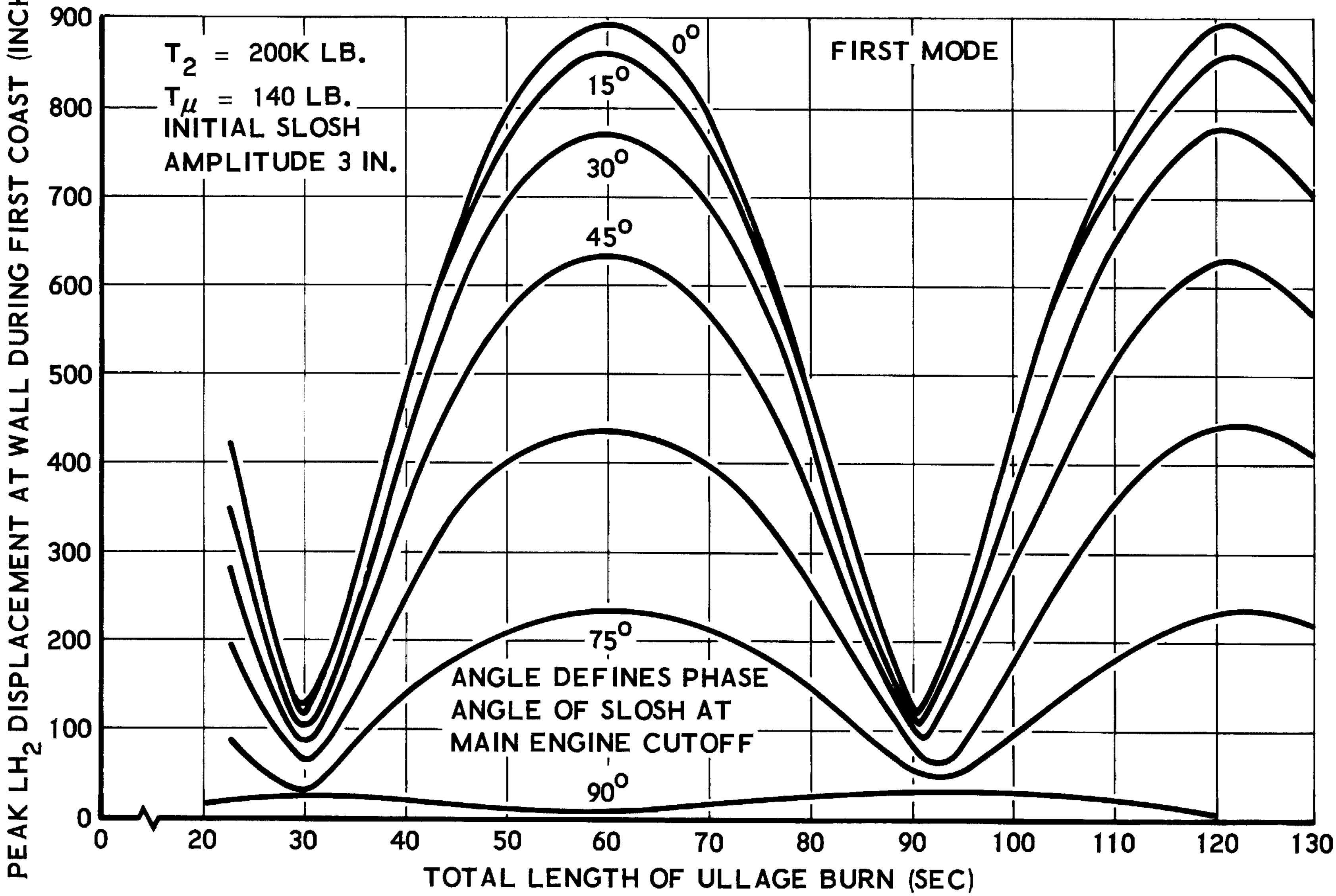


FIGURE 3

displacement during coast as a function of ullage duration for several values of slosh phase at main engine cutoff. An initial slosh amplitude (during boost) of 3 inches was used for these calculations. It can be seen that for the worst case of zero degree initial sloshing phase (maximum kinetic energy) that the peak slosh displacement is decreased from 895 to 118 inches if the ullage duration is set at 91 seconds rather than 60 seconds which is the worst case. A similar minimum exists for an ullage time of 30.3 seconds.

Figure 4 shows the time history of slosh amplitude at the tank wall for the case in which ullage thrust is terminated 91 seconds after boost thrust termination. This figure is drawn for the most adverse slosh phase at boost termination. It shows, for this case, that at ullage cutoff the sloshing frequency changes but no further slosh amplification occurs.

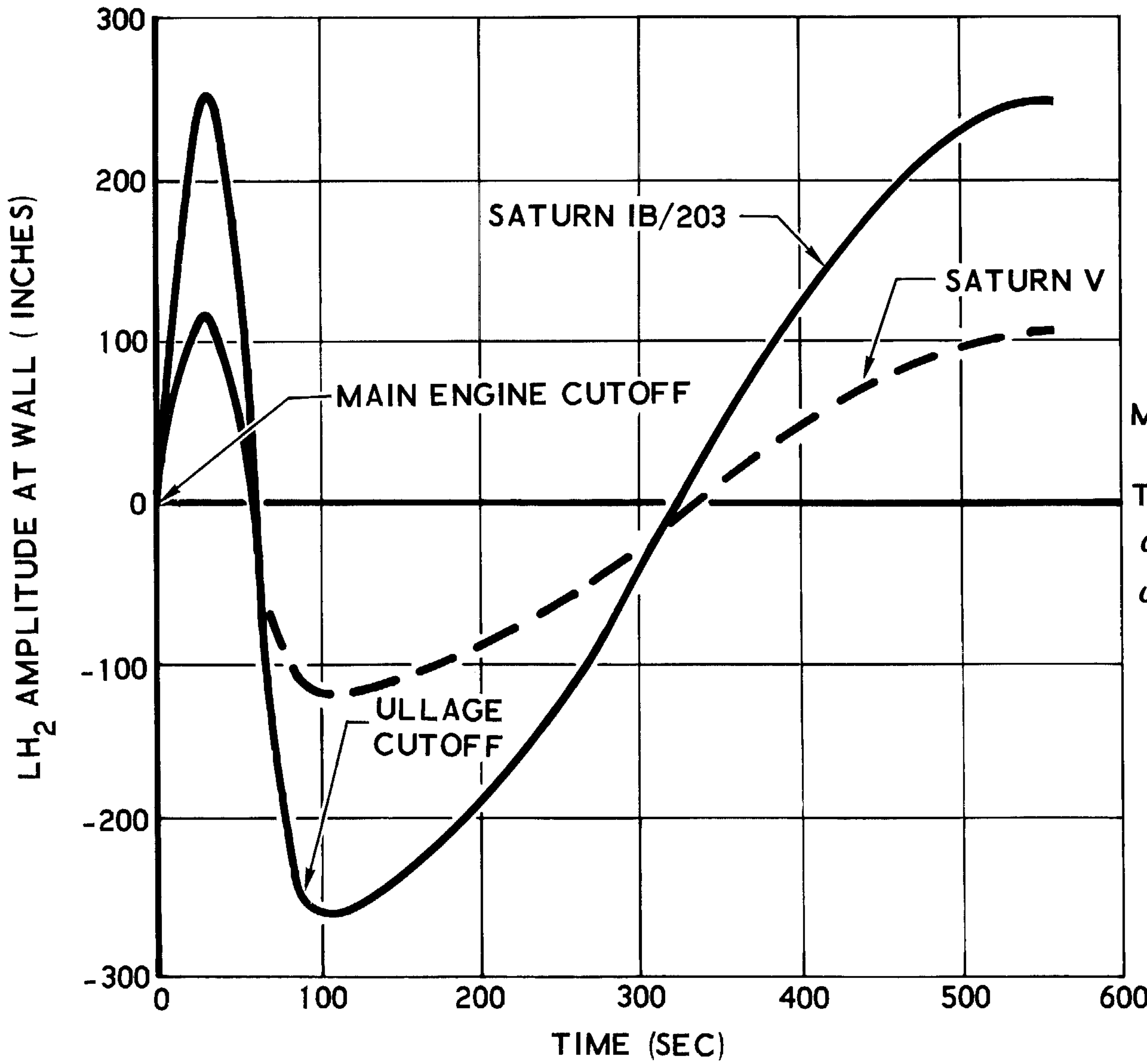
Figure 4 also shows that much greater slosh amplification will occur on vehicle 203 than on Saturn V because of the higher acceleration level prior to boost termination, and the resulting greater change in acceleration at boost cutoff. This greater amplification will be somewhat offset by the lower liquid level at cutoff on 203. The sloshing parameters used in calculating the results shown in these two figures are given in Table I.

Tolerance on ullage burntime and on ullage thrust, which will change the natural frequency of the sloshing, will increase the slosh amplification above that obtained for optimum conditions. The magnitude of these effects can be seen in Figure 2. This figure shows that a maximum increase in slosh amplitude of 10 percent is caused by a 1 percent variation in ullage burntime. Since the slosh period is inversely proportional to the square root of ullage thrust, a 2 percent tolerance on ullage thrust can cause a similar (10 percent) increase in slosh amplification. Actually, ullage burntime can be controlled very accurately so that the only significant deviation anticipated is ullage thrust.

The maximum sloshing amplification should not exceed the optimum by more than 15 percent for the expected tolerances on thrust and ullage time. Thus, a total amplification factor of 46 will be used to determine initial coast slosh amplitudes from boost slosh at cutoff for Saturn V S-IVB. A factor of 98 is indicated for S-IVB/IB-203.

LH_2 SLOSH HEIGHT VS BURN TIME (S-IV B STAGE)

OPTIMUM ULLAGE CUTOFF 30 OR 91 SECONDS - 91 SECONDS SHOWN



MAIN BOOST MAX AMPLITUDE = 3.06 N

THRUST BOOST = 200 K LB

$\omega_\mu = 0.518 \times 10^{-1}$/SEC

$\omega_c = 0.678 \times 10^{-2}$/SEC

FIGURE 4

TABLE I

S-IVB PROPELLANT SLOSHING DATA

SATURN S-IVB/V (EARTH ORBIT)

	LH_2		LOX			
	1st Mode	2nd Mode	1st Mode	2nd Mode		
Stage	Slosh Freq.(cps)	Slosh Freq.(cps)	Slosh Freq.(cps)	Slosh Freq.(cps)	Accel (ft/sec^2)	Accel (g)
Boost	0.3145	0.536	0.296	0.498	23	0.715
Ullage	0.831×10^{-2}	0.142×10^{-1}	0.782×10^{-2}	0.1319×10^{-1}	0.161×10^{-1}	0.5×10^{-3}
Coast	0.108×10^{-2}	0.184×10^{-2}	0.1015×10^{-2}	$0,171 \times 10^{-2}$	0.1535×10^{-4}	0.84×10^{-5}

SATURN S-IVB/IB (203 Earth Orbit)*

	LH_2		LOX			
Stage	Slosh Freq.(cps)	Slosh Freq.(cps)	Slosh Freq.(cps)	Slosh Freq.(cps)	Accel (ft/sec^2)	Accel (g)
Boost	0.638	1.1	0.531	1.3	111.8	3.48
Ullage	0.765×10^{-2}	0.1315×10^{-1}	0.635×10^{-2}	0.153×10^{-1}	0.161×10^{-1}	0.5×10^{-3}
Coast	0.992×10^{-3}	0.171×10^{-2}	0.825×10^{-3}	0.1985×10^{-2}	0.1535×10^{-4}	0.84×10^{-5}

* Ullage and coast accelerations for 203 assumed the same as 501.

2.1.1.3 Orbital Coast Slosh

Sloshing in a low gravity environment is characterized by larger amplitudes than are experienced during boost. This is because the restoring forces, for a given wave height, is proportional to the acceleration on the vehicle. Thus, much greater amplitudes are required to develop similar restoring forces. An indication of the low restoring force indicated by the fact that a single APS pulse, (7.5 lb-sec) causes approximately a 15 inch LH_2 wave height.

Sloshing during coast can be caused by two factors. Sloshing present during boost, which is amplified as boost thrust and then ullage thrust is terminated leaving continuous vent thrust, is the initial slosh amplitude for coast. The action of the attitude control system during coast will cause motion of the vehicle both laterally and angularly. This vehicle motion will, in turn, excite propellant sloshing. The magnitude of this induced sloshing will depend on the relationship between the limit cycle frequency of the attitude control system and the natural sloshing frequency, and the slosh damping in the tank.

Because the frequency of APS firings in any axis is a function of the disturbances in that axis, a single limit cycle frequency cannot be determined for each axis. The determination of slosh amplitudes is further complicated because of cross axis coupling, the random distribution of initial conditions and disturbances, the closed loop nature of the vehicle and slosh coupling, and the nonlinearities inherent in the system.

Sloshing during coast has been studied for the 203 LH_2 experiment configuration, with an analog computer simulation which includes a five degrees of freedom vehicle, first and second mode hydrogen sloshing in both the pitch and yaw axes, and the attitude control system.

Numerous simulation runs, each equivalent to a 4-1/2 hour orbital coast period, have been made to determine the magnitude of sloshing expected during orbital coast. These simulations have studied the effects of variations in initial sloshing magnitude, initial attitude, aerodynamic parameters, disturbances, and slosh damping.

The simulations shows that the maximum sloshing amplitudes experienced during a 4-1/2 hour mission varies widely with variations in the parameters mentioned above, and in fact, small variations in these parameters resulted in large variations in the maximum slosh amplitude. The natural frequency of first mode hydrogen sloshing is very low such that only about 30 complete sloshing cycles will be obtained during a full 3 orbit flight. Because of this fact, and of the presence of cross axis coupling, steady state limit cycling conditions were never reached. The randomness of aerodynamic disturbances, platform drift, impulse magnitude per control pulse, and the spacing of maneuvers which is expected in flight will result in flight histories which are even more random than those of the simulations. This indicates that a statistical approach must be taken to determining sloshing amplitudes during orbit. The runs made to date, which include studies of several baffle configurations, do not represent an adequate statistical sample.

Preliminary results of the simulations indicate that first mode hydrogen slosh in pitch and second mode hydrogen slosh in yaw experience the greatest amplitudes. Table II includes a summary of runs made to date, and indicates the variations in slosh amplitudes resulting from variations in some of the parameters.

The largest slosh amplitudes recorded from the simulations are 480 inches of first mode slosh height at the tank wall 132 inches of second mode height at the peak of the wave. These particular runs were for cases which had slosh damping representative of a smooth walled tank. The exact damping which would be provided by partially submerged baffles under the very low acceleration conditions with the resulting low frequencies and velocities is difficult to predict. These slosh amplitudes are currently being used for baffle design and vent analysis.

2.1.2 Design Approaches Considered

Two basic approaches to the problem of minimizing venting of liquid were studied. One method relies on a liquid/gas separator to prevent venting of liquid but may include slosh baffles or deflectors to minimize the amount of liquid impinging on the separator. The other approach relies on slosh baffles and/or deflectors to prevent or minimize the amount of propellant

TABLE II

203 LH_2 SLOSH ANALYSIS

RANGE OF PARAMETER VALUES AND SLOSH HEIGHTS

TYPICAL PARAMETERS			MAX VARIATION	
	NOMINAL	UNITS	VALUE	UNITS
APS PW	.050	SEC	0	
APS THRUST	150	LBS	0	
AERO DIST	.50	$\frac{\text{FT-LB}}{\text{DEG}}$	±.25	$\frac{\text{FT-LB}}{\text{DEG}}$
GRAVITY DIST	.14	$\frac{\text{FT-LB}}{\text{DEG}}$	0	
PLATFORM MISALIGN	0	DEG	±1,±2,±3	DEG
PITCH-YAW INITIAL RATE	$.12 \times 10^{-3}$	$\frac{\text{RAD}}{\text{SEC}}$	±100%	$\frac{\text{RAD}}{\text{SEC}}$
ROLL INITIAL RATE	$.51 \times 10^{-3}$	$\frac{\text{RAD}}{\text{SEC}}$	±100%	$\frac{\text{RAD}}{\text{SEC}}$
INITIAL SLOSH DISP	100	IN	±100	IN
FIRST MODE DAMPING	.2	%	+3.0	%
SECOND MODE DAMPING	.2	%	+1.0	%

SLOSH PARAMETER	MINIMUM OF MAXIMUM SLOSH HEIGHT/MISSION	MAX SLOSH HEIGHT
FIRST MODE HYDROGEN	47 IN	480 IN
SECOND MODE HYDROGEN	65 IN	133 IN

reaching the vent so that a liquid/gas separator is not required. This section will discuss some of the configurations which were studied.

2.1.2.1 Deflectors (Figure 5)

One of the configurations considered was that of simple deflectors installed in the ullage space. The purpose of these deflectors was to catch the liquid and direct any waves back into the main fluid body, rather than suppress the waves at the onset. Problems associated with this design are that large waves may inundate the system and that the deflector does not suppress waves initially. Further, little or no damping in the slosh modes is obtained from this particular configuration. In addition, it was felt that any liquid which rose above the deflector during the low acceleration environment encountered in orbit, might be trapped there by surface tension and aerodynamic forces caused by vent flow velocities.

Ullage deflector effectiveness is largely a function of the hole diameter. For a proposed deflector with a six foot diameter central hole, the flow of liquid from above the baffle to below is very slow. At 2×10^{-5} g and no boil-off, approximately 56 seconds is required for 25 cubic feet of liquid to flow through the hole. Since it is expected that 0.3 lb/sec of vapor will be flowing upward at the same time, the 56 seconds number is much too low. Actual drain rate is difficult to predict, but an idea of the problem is gained by comparing the dynamic pressure of the flowing gas with the hydrostatic pressure of the pool of liquid trying to flow through the hole:

Gas Dynamic Pressure = 1.7×10^{-5} psf

Liquid Hydrostatic Pressure = 1.3×10^{-6} psf

Thus, an order of magnitude favors the gas flow.

For the same configuration, the upward flowing gas will cause liquid globules smaller than about 2.5 inches in diameter to be carried with the stream toward the vent. It is not hard to visualize that venting gas meeting with liquid with a downward motion will produce some droplets.

Such a deflector would completely obscure the view of the tank wall by the TV cameras in the 203 experiment. It is very difficult to observe the

BAFFLE CONFIGURATION

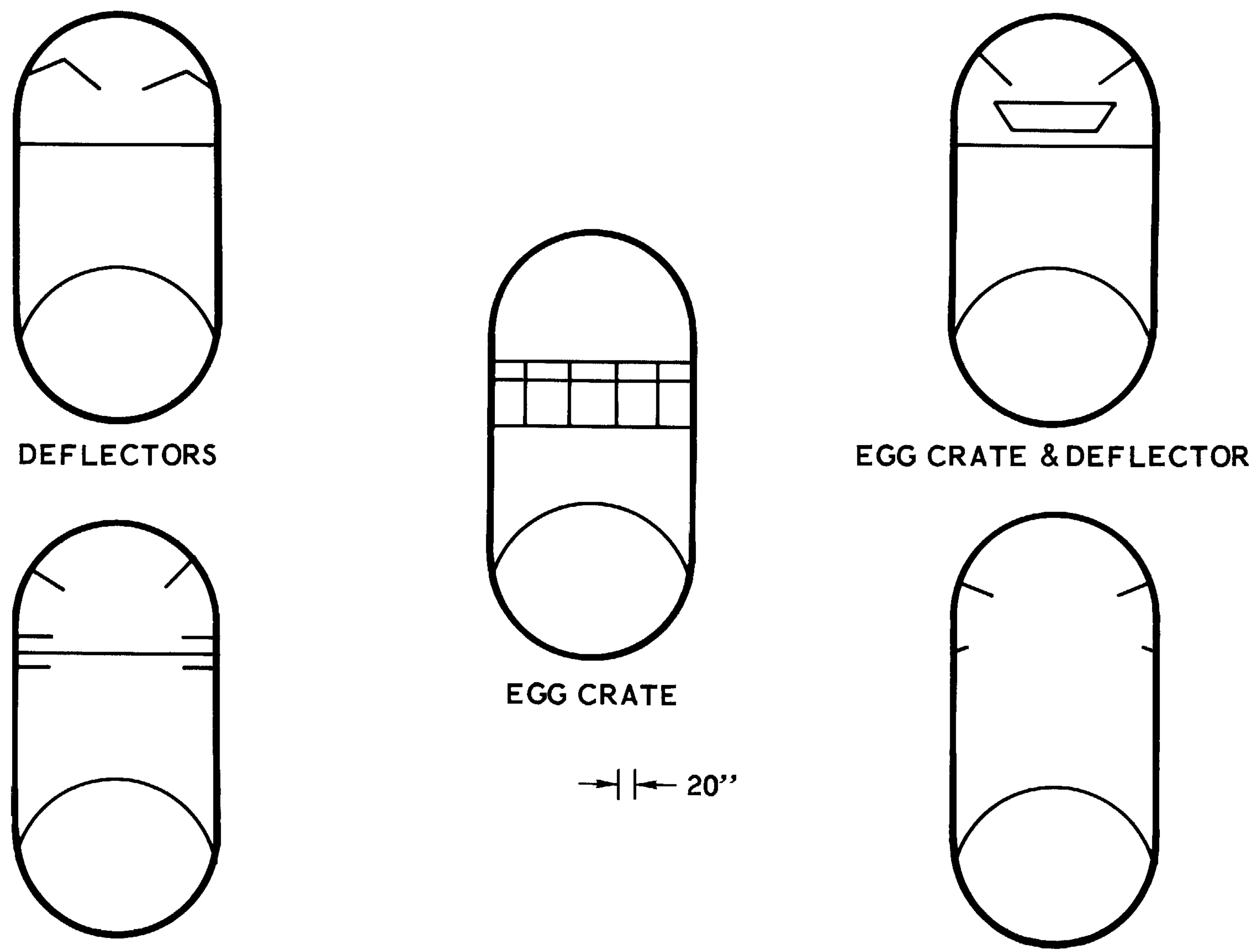


FIGURE 5

behavior of the liquid from above with intersection of the liquid and wall for reference.

A smaller deflector in the ullage with a minimum open hole of 12 feet in diameter appears reasonable, however. Superimposing expected orbital slosh waves for a deflector of this length indicates that only small amounts of liquid will pass through the open area of the deflector. TV camera viewing is only impaired in the sense that light intensity is somewhat reduced. Also the lesser effectiveness of the small deflector must be compared with the reduction of the entrainment problem.

2.1.2.2 Ring Baffles and Deflector (Figure 5)

One of the most promising designs is the simple ring baffle design with deflectors. These baffles would be in the form of annular rings attached to the wall and extending out from the wall. The baffles would be located at or near the free surface liquid level. One or more baffles may be required depending on the total amount of damping that may be required to suppress initial transients and sloshing.

Ringbaffles located below the liquid level offer some advantages. They do not impede the flow of boil-off gases nor channel liquid into the path of the upward flowing gas. They do not trap liquid up in the ullage space. The field of view of the TV cameras and intensity of lighting are not impaired. The chief objection to sub-surface baffles is that they tend to trap vapor bubbles and thus increase the liquid surface rise. They also increase the heat flux to the tank due to their fin effect. Multiple baffles increase both of these adverse effects.

Bubble entrapment considerations require that only one baffle be used. A deflector would be included to stop large waves at shutdown and during orbital coast. Considerable work has been done on this type of baffle by NASA and other groups, so that performance during boost may be predicted with good results. The damping provided for large amplitudes when partially submerged at low accelerations is more nebulous. The chief disadvantage of this particular arrangement is that it may tend to trap bubbles and impede the movement of the bubbles to the ullage space and thus increase surface rise. Buoyant forces are quite small during coast; as a result, any obstruction that tends to impede bubble motion may be detrimental to vent operation. A multiple ring baffle design would require work to determine the total volume of bubbles that might be trapped and the effect of this on system performance. A multiple baffle arrangement is considered to be more apt to trap bubbles than is a single baffle because the thermal convection currents will not be as effective in removing bubbles from under the upper baffles. The prime advantage of this system is the simplicity and low weight for the amount of fluid motion damping produced.

2.1.2.3 Egg Crate Baffles (Figure 5)

Egg crate baffles were examined, but few advantages were found. The average egg crate baffle produces little damping unless it is fairly deep. A deep baffle would have a large surface area and might entrap a large volume of hydrogen bubbles. Also, the egg crate design would not catch any fluid should any wave motion occur at cutoff. In other words, a deflector would be required as a back-up device, in that an egg crate only suppresses motion, and would not act as a deflector if fluid motion were to occur. In addition the Bond number resulting from the egg crate design was considered unacceptable from bubble considerations.

2.1.2.4 Egg Crate and Deflector (Figure 5)

This configuration consists of an egg crate type baffle located in the center of the tank ullage space with a deflector located above it on the tank wall. This configuration offered good control of the cutoff wave and other large amplitude slosh because of the turbine like action of the double vanes. It also provides good control of second and higher slosh modes. However, even a single lower ring was believed to be detrimental from bubble entrapment considerations.

2.1.2.5 Baffle Plus Deflector (Figure 5)

The most promising configuration to date considering both damping criteria and bubble restrictions is a combination ring baffle and splash deflector. This particular design combines the advantages of the baffle with those of the deflector. The ring baffle suppresses waves at the onset by providing damping during boost. The deflector acts as a backup device to catch liquid that gets past the ring baffle. A deflector with a small open area is desirable to deflect wave motion caused by second mode slosh however, other considerations may determine the size of the opening. The ring baffle damps the first mode primarily, with less effect on second mode slosh. As a result, it is possible that waves due to second mode could occur that would not be damped by the ring baffle. The splash deflector would serve as the back-up device to contain some of the liquid in these waves. The single baffle is preferable to multiple baffles based on bubble considerations discussed previously.

2.1.2.6 Screens

Screen type devices located near the surface of the liquid have been studied and offer possibilities. A screen mesh will tend to act as a barrier because of surface tension and contain waves induced at cutoff and during coast. For a fluid mass with a given velocity, a screen arrangement will tend to stop the motion and direct the slosh back into the liquid bulk. It is apparent, however, that for sufficient impact velocities, a portion of fluid may escape through the screen. The main problem with a screen-type separator is the lack of engineering understanding as to what might occur, since there are more variables involved with a design of this type. Any liquid that got past the screen might be trapped there and then be discharged through the vent system. The addition of baffles below the screen will minimize the quantities of liquid striking the screen and the velocity with which it strikes the screen.

A fine mesh screen placed across the diameter of the fuel tank somewhat above the liquid level would achieve the following:

1. Prevent slosh waves and large entrained liquid globules from entering the upper portion of the tank and thus:
    a. Reduce boiloff caused by liquid in contact with the relatively hot ullage walls.
    b. Reduce the amount of liquid that is vented with the continuous vent gas.
2. Damp slosh waves.
3. Allow boiloff gas to pass through.

At low gravity conditions body forces are reduced in magnitude allowing surface tension forces to become more significant. The criteria for the relative importance of the two forces is the Bond Number

$$Bo = \frac{\rho g d^2}{\sigma} \tag{1}$$

where

ρ = fluid density

g = acceleration or gravity

d = typical dimensions

σ = surface tension

For Bond Num much greater than unity body forces are dominant while for $Bo << 1$ surface tension is dominant.

The pressure differential supported by the surface tension at the interface of a gas and liquid for a round or square opening is:

$$\Delta P = \frac{4\sigma}{d} \tag{2}$$

Equation 2 shows that the pressure differential increased with decreasing opening size. Screens are, therefore, ideal since they provide small openings for large total area.

For a pressure difference where the pressure on the liquid side is greater than on the vapor side there is a real question as to the holding ability of a screen due to the possibility of the meniscuses of the individual openings combining into one large meniscus capable of supporting virtually no pressure differential. Investigations are continuing in this area.

The ability of a screen to separate liquid entrained in a flowing gas stream is probably best determined by the magnitude of the Weber number. This dimensionless parameter is the ratio of dynamic forces to surface tension forces:

$$We = \frac{\rho v^2 d}{\sigma}$$

For We $>$ 1 dynamic forces dominate while for We $<$ 1 surface tension is dominant.

Since the typical dimension "d" is to the first power in the Weber Number and squared in the Bond Number, it is expected that the Weber Number will be the critical parameter in determining the critical dimension "d".

A screen is useful as a damping device even in the absence of a liquid-vapor interface. Liquid flowing through the screen experiences a high loss in total head, the loss being proportional to the square of the velocity.

2.1.2.6.1 Mesh Sizing

The anticipated acceleration level during orbital coast is 2×10^{-5} g's. Slosh velocities induced after first burn cutoff are anticipated to be less than one ft/sec. Gas velocity through a localized 0.1 ft^2 area of the screen is also less than one ft/sec. Therefore, the Weber Number is based on this velocity. For

$$We = 1, D = .006 \text{ inch.}$$

The corresponding Bond Number is 3.31×10^{-7}.

2.1.2.6.2 "W" Screen With Vent Below

The screen could be placed in the tank with the vent line extending through the screen as in Figure 6 so that venting takes place between the screen and liquid. The pressure would be slightly less in the space below the screen than above. This would make the screen a good slosh baffle. Most liquid drops expelled by the bulk due to bubble breaking or slosh would impinge on the screen, instead of the hot walls, and return to the bulk. Some droplets would enter the vent directly, however. The "W" shape of the screen is to keep the liquid run-off from the screen away from the vent entrance while providing good slosh damping.

2.1.2.6.3 Conical Screen With Vent Above

Placing the tank vent above the screen as in Figure 7 has the advantage that any liquid globules entrained in the gas cannot pass through the screen. The

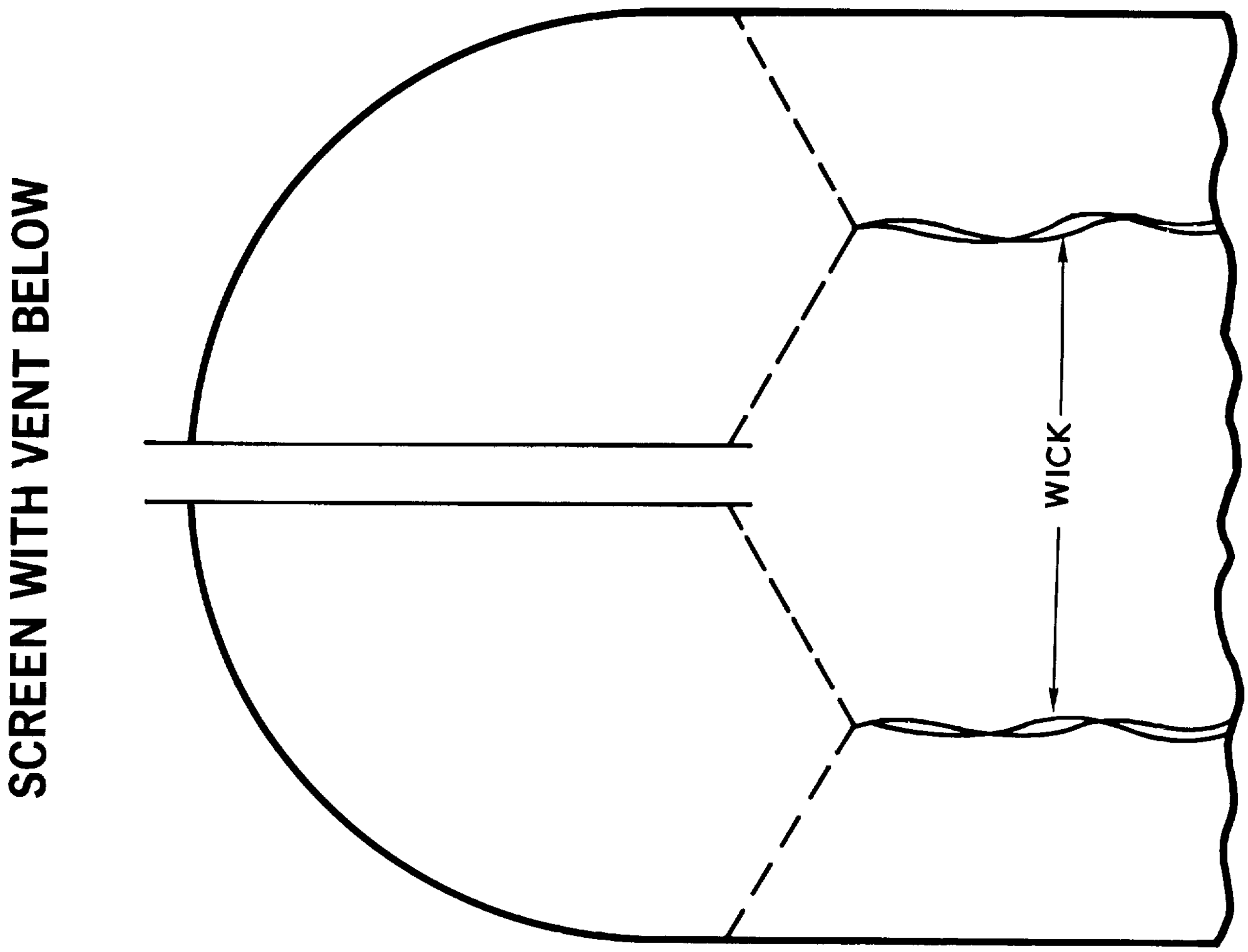


FIGURE 6

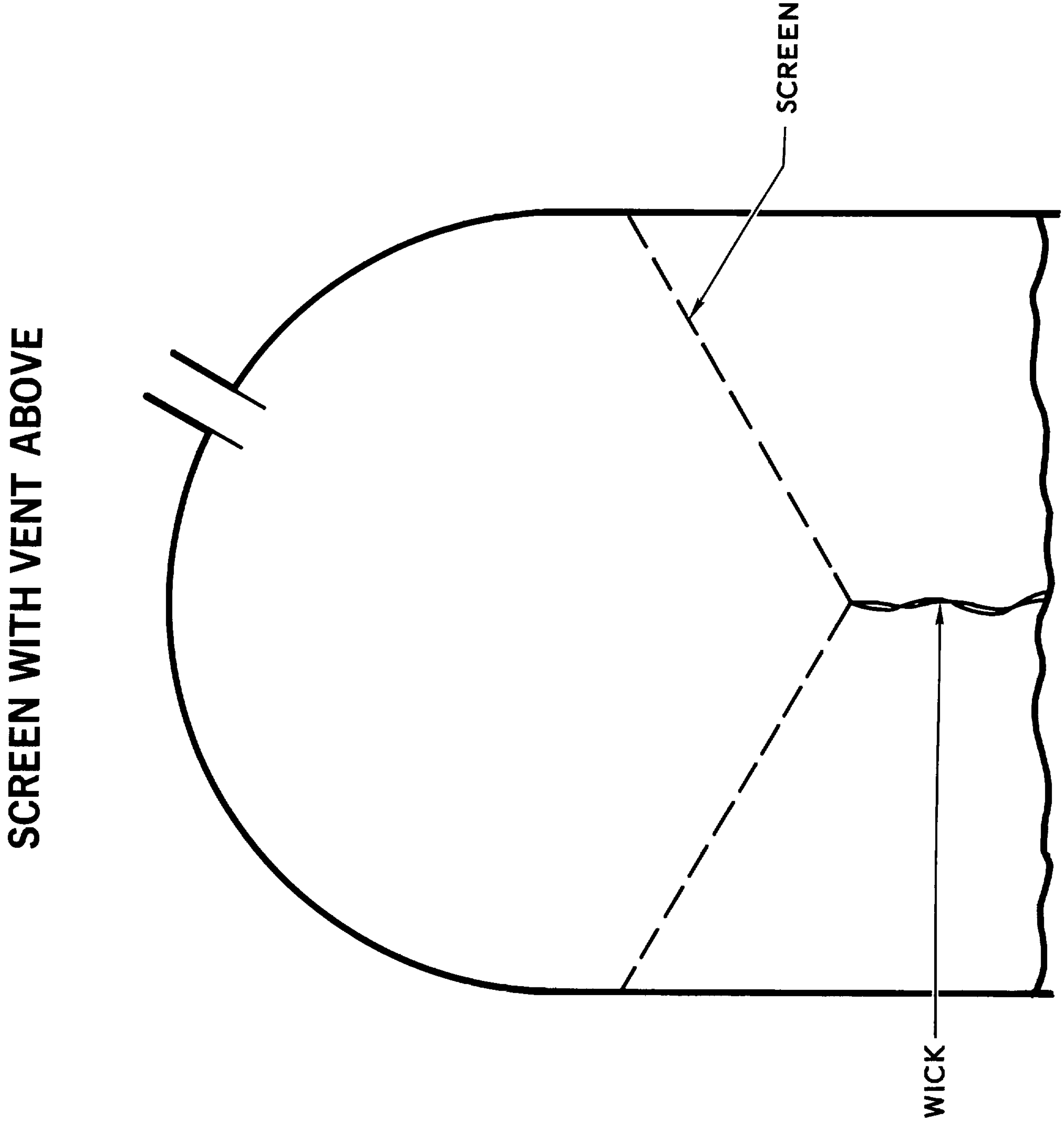


FIGURE 7

screen, therefore, acts as an efficient liquid-vapor separator. The conical shape causes the screen to damp slosh effectively.

Placing the tank vent above the screen has some disadvantages. Any liquid that gets through the screen will stay above the screen until it boils away or until restart. There is virtually no possibility of it returning to the bulk during coast due to the liquid holding properties of the screen.

Some liquid can get through the screen by being carried with the boiloff and by flow during submersion by a slosh wave; especially a boost slosh wave. If a wick is used to wet the screen, there is the possibility that the pressure differential across the screen will actually pump liquid from the bulk.

2.1.2.6.4 "W" Screen With Vent Switching

Since there is the possibility that an excessive amount of liquid could accumulate above the screen it seems advisable to incorporate in the system an alternate vent line. This "built-in backup" system would consist of an additional vent line with its entrance below the screen as in Figure 8. With the dome vent closed, a negative pressure differential would be induced across the screen due to gas flow from beneath. The liquid would then be driven back into the lower space. Switching to the alternate vent would be actuated by a liquid-vapor sensor located at a pre-determined height above the screen. Return to normal venting would be signaled by a second sensor or by pre-set time interval. Venting from under the screen could result in some loss of entrained liquid, although probably not any more than for a dome vent without screen.

2.1.3 Proposed Solution

The proposed solution to control venting of liquid hydrogen relies primarily on control of liquid motion rather than on a liquid/gas separator. The control of liquid motion after orbital injection reduces to the problem of minimizing boost slosh just prior to cutoff, minimizing amplification of boost slosh at J-2 thrust and ullage thrust termination, and limiting slosh amplitudes during coast. Therefore a three fold complimentary solution is proposed.

SCREEN WITH VENT SWITCHING

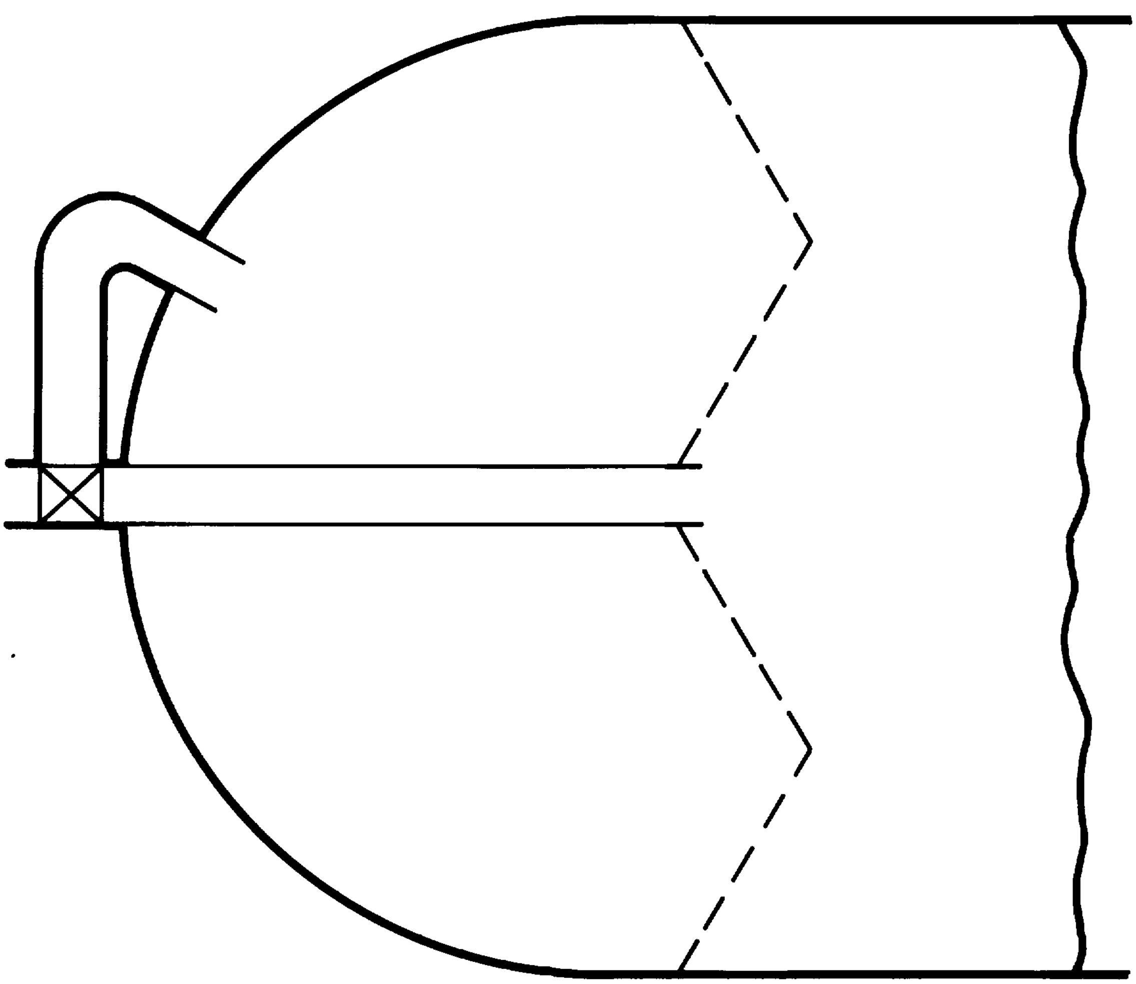


FIGURE 8

1. Provide boost slosh baffles to attenuate as much as practical the sloshing occurring during S-IVB burn. As discussed previously this solution is only practical for the singular type excitations occurring at S-IVB separation. Even with baffles residual sloshing can be expected at engine cutoff primarily due to control system limit cycle oscillations.

2. Minimize slosh wave amplification at ullage thrust termination by timing the ullage burning time to minimize the maximum total slosh amplification at boost termination which is the product of the amplifications occurring at boost and ullage terminations. This can be practically accomplished by pre-selection of the ullage burntime to be equivalent to 1/4 or 3/4 of one slosh period. Thus, for worst slosh conditions existing at J-2 engine shutdown the ullage thrust will be terminated at the optimum time in the slosh cycle. Deviations from the worst slosh condition at J-2 engine cutoff will yield lower than maximum cutoff wave height.

3. Provide a deflector above the slosh baffle to deflect the large amplitude waves expected at cutoff and during coast. The configuration of the deflector and baffle is shown in Figure 5.

These three solutions in combination will minimize the LH_2 wave motion at injection into orbit on the Saturn V. Figures 9, 10 and 11 show the cutoff waves predicted for S-IVB Saturn V and 203 respectively. Although the wave height without the deflector is excessive, tests made with small models with a similar deflector indicated that the deflector was effective in keeping most of the liquid in waves of this magnitude away from the vent. Tests with the exact configuration will be required to confirm the design and determine the amount of liquid passing the deflector. Due to the relatively large acceleration on IVB/203 a larger cutoff wave can be expected. Although the lowered LH_2 level at cutoff makes a somewhat higher wave tolerable, the wave height expected, as shown in Figures 2 and 11, will result in 203 being a conservative test of Saturn V.

WAVE MOTION AT ENGINE SHUTDOWN DUE TO A 3 INCH WAVE EXISTING PRIOR TO SHUTDOWN

A) FIRST MODE

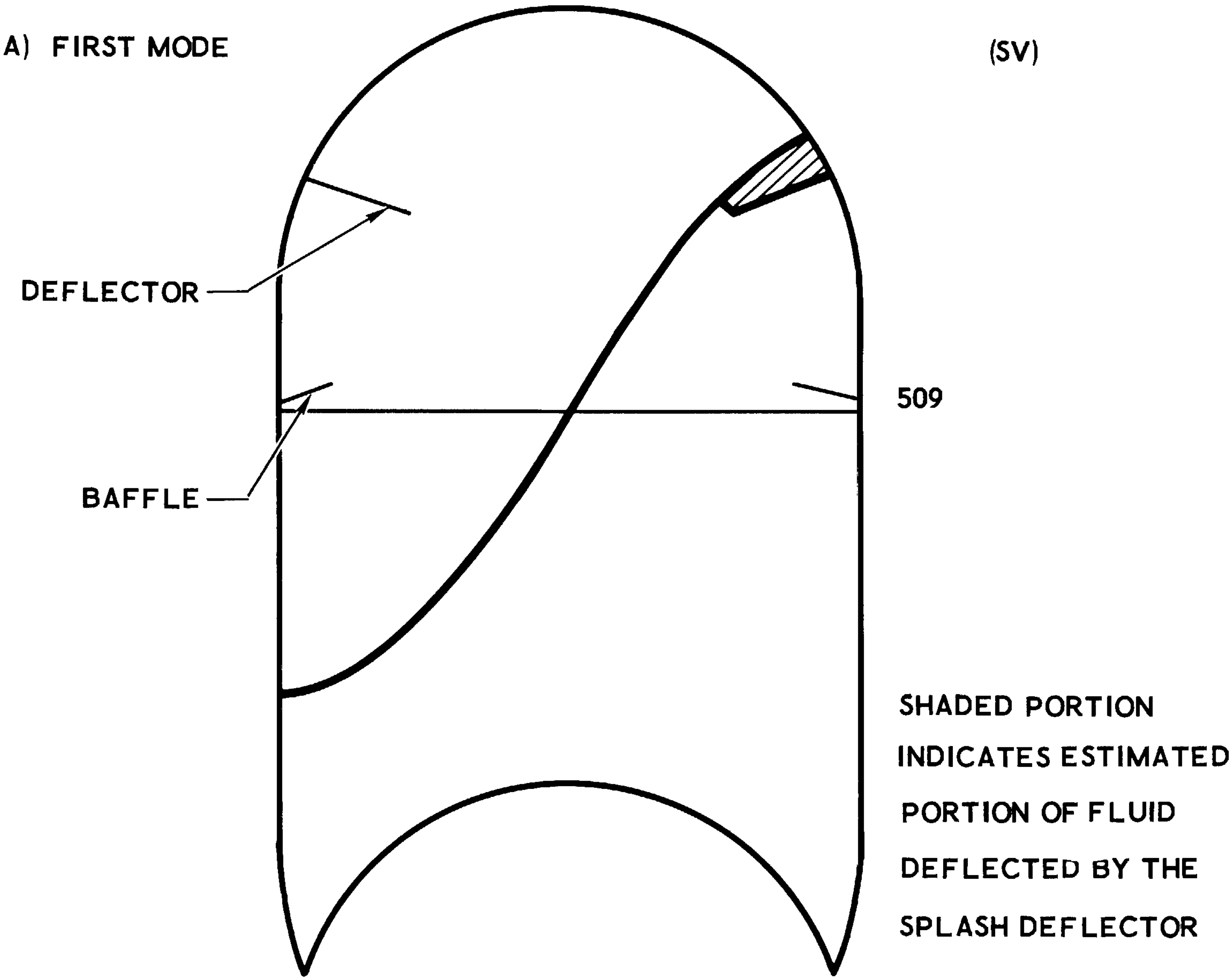


FIGURE 9

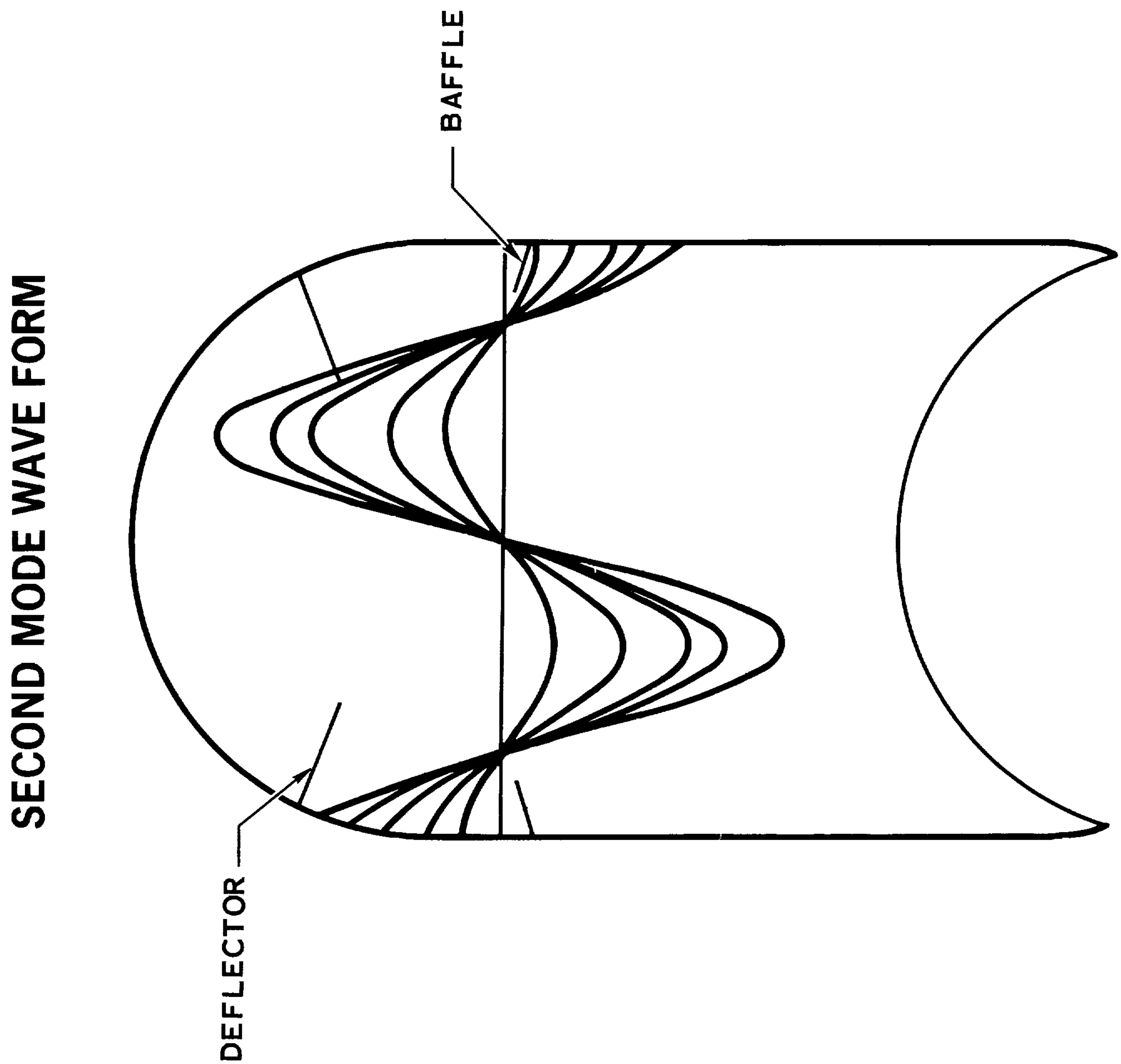


FIGURE 10

WAVE MOTION AT ENGINE MOTION DUE TO A 3 INCH WAVE EXISTING PRIOR TO SHUTDOWN

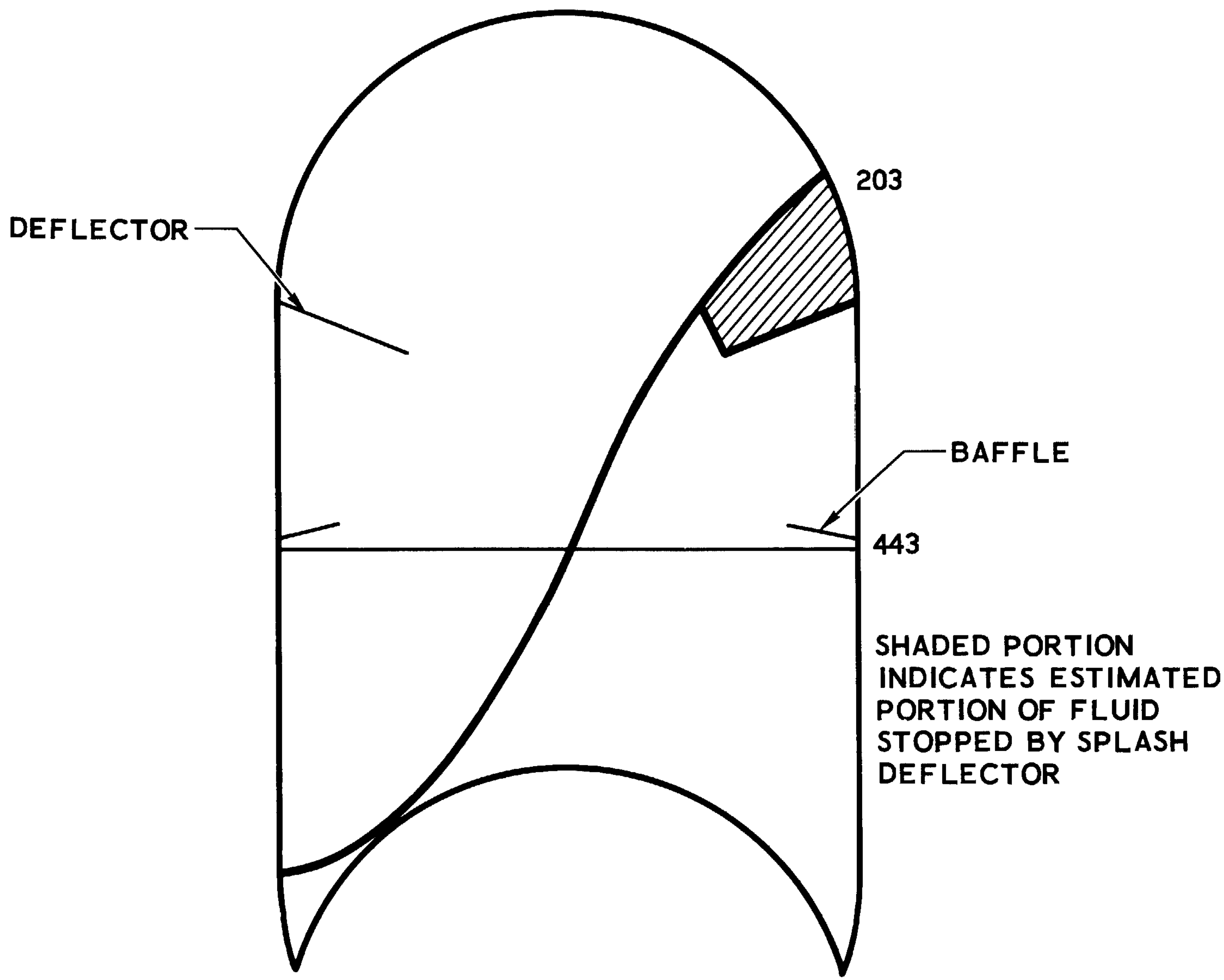


FIGURE 11

2.1.3.1 Slosh Baffle Damping Requirements

The following anticipated S-IVB conditions were used to determine slosh baffle damping requirements.

1. An initial LH_2 slosh wave height caused by remaining lower stage slosh and by the separation transient of ±6 inches wave height at the tank wall was used. This value is based on an extrapolation of S-IV flight test results. S-IVB/IB analyses have indicated a value of ±12 wave height. The lower S-IV value has been chosen as a more representative value for Saturn V. The S-IVB/IB analytical results were based on combined worst possible disturbances existing at separation.

2. Time from separation to first cutoff (earth orbital injection) on IVB/V is approximately 150 sec. This time is used as the maximum allowable time to diminish the slosh wave.

3. An allowable cutoff slosh amplitude caused by initial slosh excitation only of ±.25 inch has been chosen as a sufficiently small value which will not contribute significantly to the cutoff wave.

4. The natural (un-baffled) LH_2 damping ratio provided in the tank is predicted to be 0.003. This value has been extrapolated from S-IV flight test data and an additional amount added to account for damping provided by the deeply submerged baffles. It is believed this value is more realistic than the lower, more conservative, value used in control system design, which does not consider damping provided by surface roughness, helium spheres and other items in the tank.

5. The damping provided by the deflector was neglected.

From these conditions the slosh damping requirements have been determined as a function of time of damping action, with maximum damping action time allowed of 150 seconds (time from separation to first cutoff). This method yields as expected relatively low damping requirements acting for long times, and relatively high damping requirements acting for short times. The results of this analysis are shown in Table III.

TABLE III

SLOSH BAFFLE DAMPING REQUIREMENTS

TIME DURATION OF EFFECTIVE BAFFLE ACTION	TIME FROM SEPARATION TO START OF DAMPING	REQUIRED DAMPING RATIO	AVERAGE SLOSH AMPLITUDE DURING BAFFLE ACTION TIME
150	0	0.01124	3.125
125	25	0.01288	2.723
100	50	0.01536	2.387
75	75	0.01948	2.087
50	100	0.02772	1.829
25	125	0.05236	1.607
15	135	0.08473	1.523

2.1.3.2 Slosh Baffle Design

The slosh damping requirements as a function of time of action can be used to establish the required number of slosh baffles and the slosh baffle dimensions. Baffle spacing can be introduced as a parameter in this calculation. This has been done assuming the straight forward efficient ring baffle solution.

The baffles necessary to gain the required damping were calculated by Miles ring baffle formula:

$$\zeta = 2.83e^{-4.6\ d/R}\ a^{3/2}\ (\eta_{w/R})^{1/2}$$

$$\zeta = c/c_c$$

d = Submersion depth

R = Tank Radius

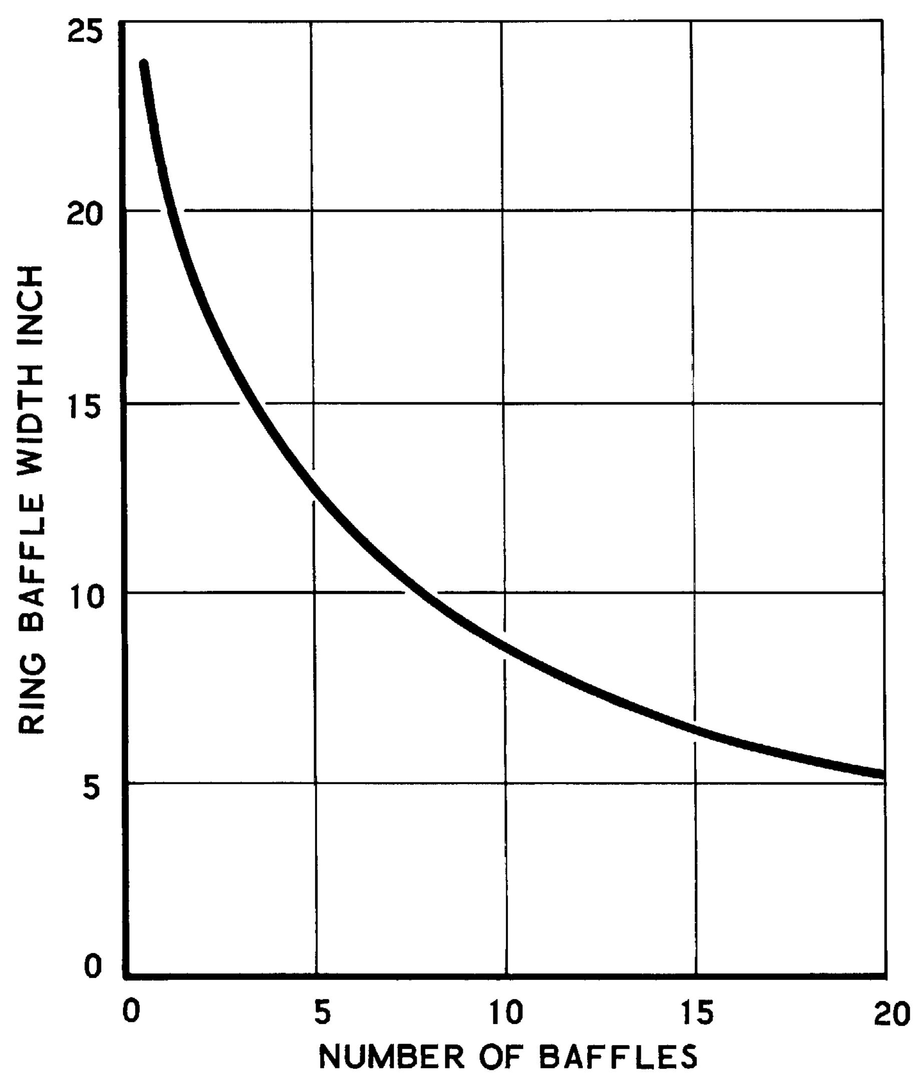
η_w = Slosh Amplitude

$a = (2RW - W^2) \div R^2$

W = Baffle Width

Superposition of the damping from the multiple baffles was assumed. The results in terms of baffle width versus number of baffles required is shown in Figure 12. Although multiple baffles are feasibly during boost, bubble

BAFFLES REQUIRED TO DIMINISH BOOST SLOSH FROM ±6 INCHES AT J-2 IGNITION TO ±1/4 INCHES AT J-2 CUTOFF



BAFFLES ARE NORMAL RING BAFFLES WITH LOWEST RING AT 3 IN BELOW MAX C/O LIQUID LEVEL AND REMAINDER EQUALLY DISTRIBUTED OVER REQUIRED RANGE OF DAMPING

S-IVB/SAT V

FIGURE 12

considerations during orbital coast require that only one baffle be used. Figure 12 shows that a 22.5-inch baffle width is required to satisfy the design requirements.

2.1.3.3 Slosh Considerations for Design of Tank Hardware

Previous studies have indicated that maximum slosh pressures on the LH_2 tank during boost will be 0.1 psi. This is based on assumption of a 24-inch slosh wave height. Figure 13 shows the separation pressure distributions. Additional data on slosh environment to be used for design for the cutoff and coast slosh conditions is presented in this section.

Figures 14 through 16 define the velocity fields and pressure fields in the upper portion of the LH_2 tank. These plots show the pressures that would be exerted on any separate screen, baffle, or deflector that might be installed in the ullage space. Also shown are the velocity fields.

All profiles are due to sloshing alone. These represent the best estimates at present on wave heights and frequencies.

Figures 14 and 15 represent environmental conditions which will yield design criteria at engine shutdown. If the engine is shut down while any sloshing motion is occurring, the momentum of the fluid will tend to cause the fluid to continue in its upward path. This will occur one time, since the fluid will eventually impact the forward dome (or screen, baffle, deflector, etc.) thereby expending the energy in this particular mode.

Figure 16 represents a steady state condition that would exist after the transient phenomena described above were suppressed. It represents the peak pressures and velocities that would occur due to the first slosh mode in the coast condition. Thrust at this time is quite small; as a result, the fluid mass sloshes very slowly and at relatively large amplitudes. Approximately 30 cycles of this mode could occur during the 4-1/2 hour coast period.

It is noted that Figure 16 (2nd mode at cutoff) produces the most severe design conditions, velocities and pressures for the other conditions are

DESIGN VELOCITIES AND PRESSURES AT STAGE SEPARATION

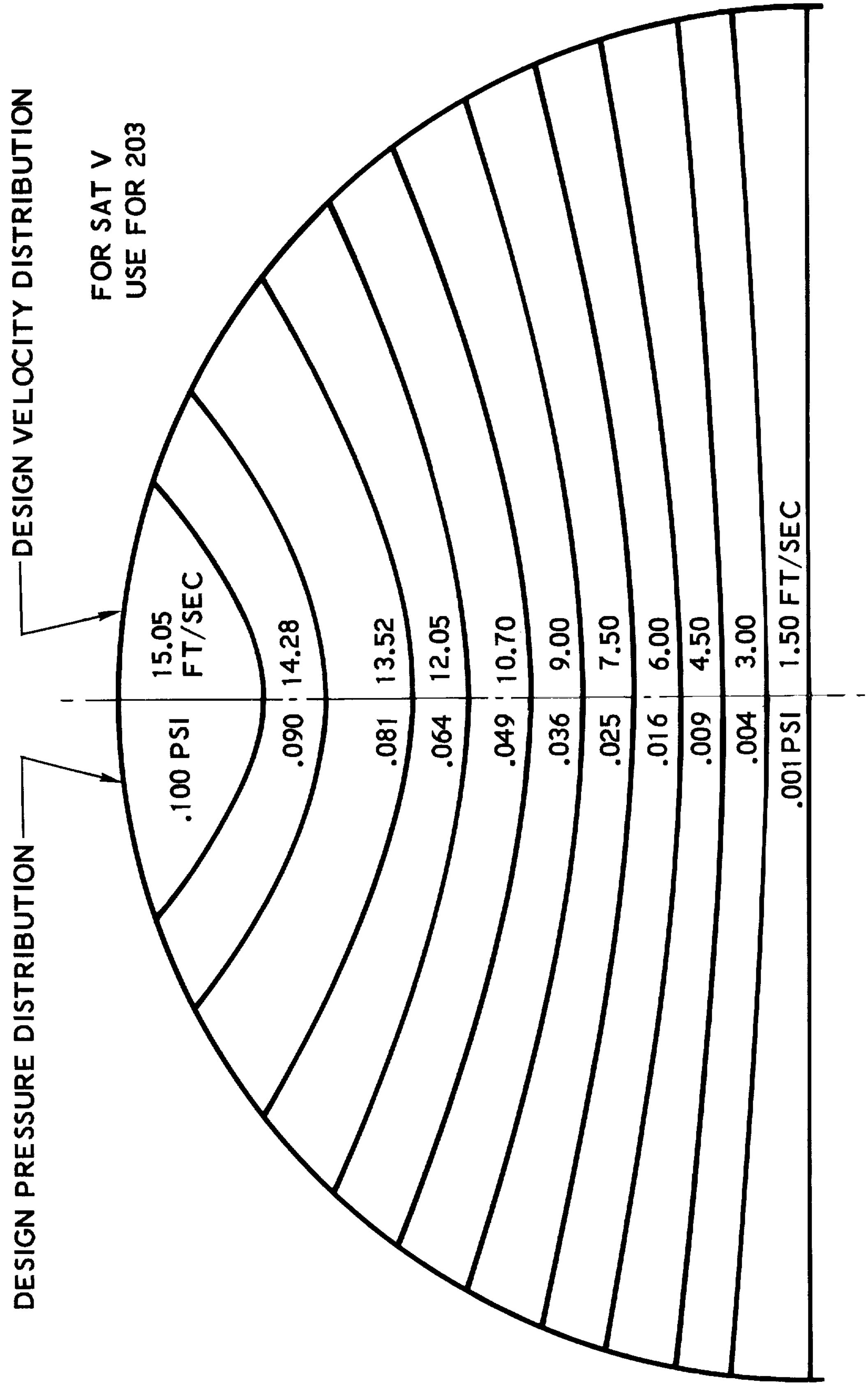


FIGURE 13

PRESSURES AND VELOCITIES
DUE TO 1ST SLOSH MODE AT ENGINE CUT-OFF

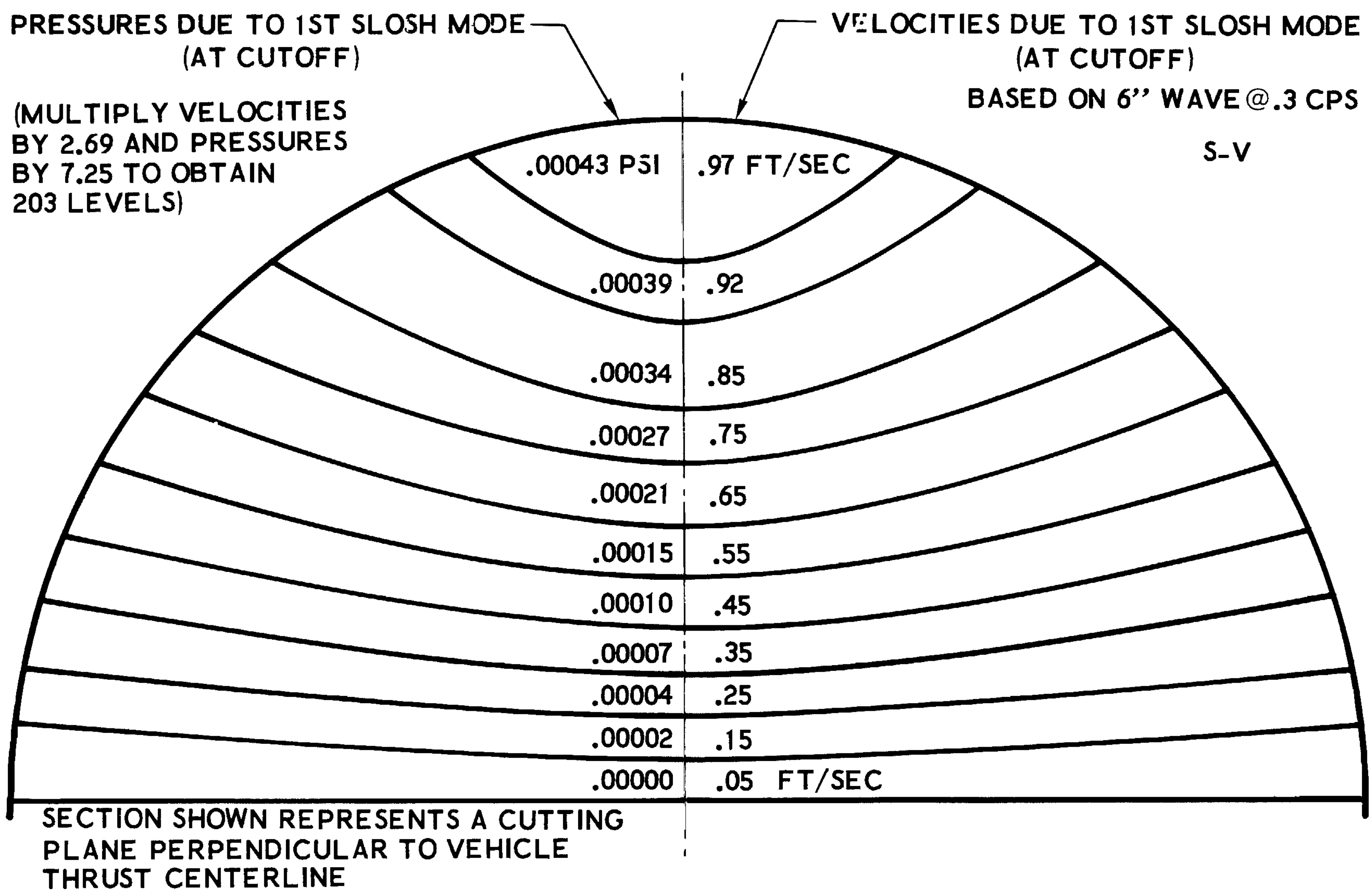


FIGURE 14

PRESSURES AND VELOCITIES DUE TO 2ND MODE SLOSH AT ENGINE CUT-OFF

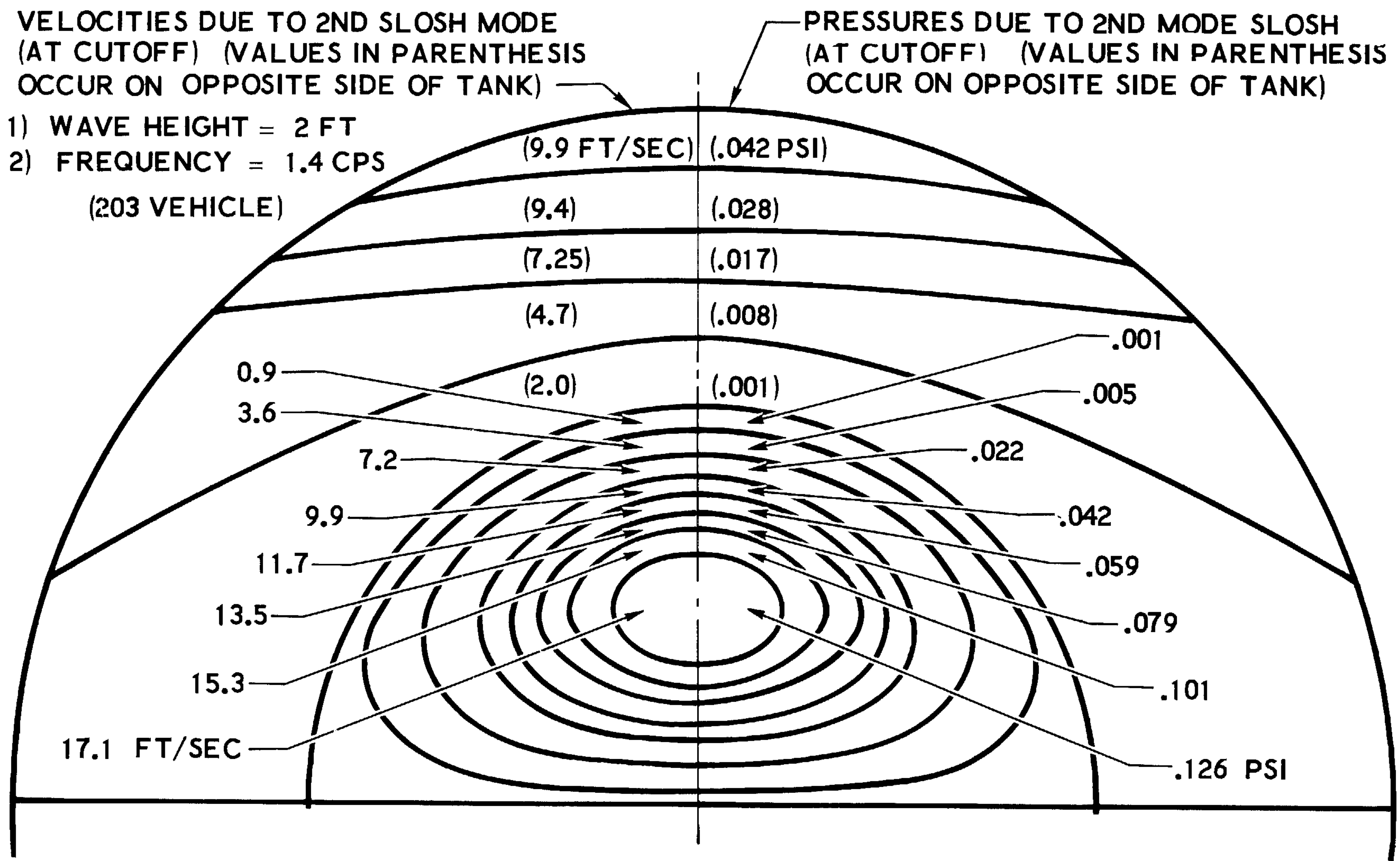
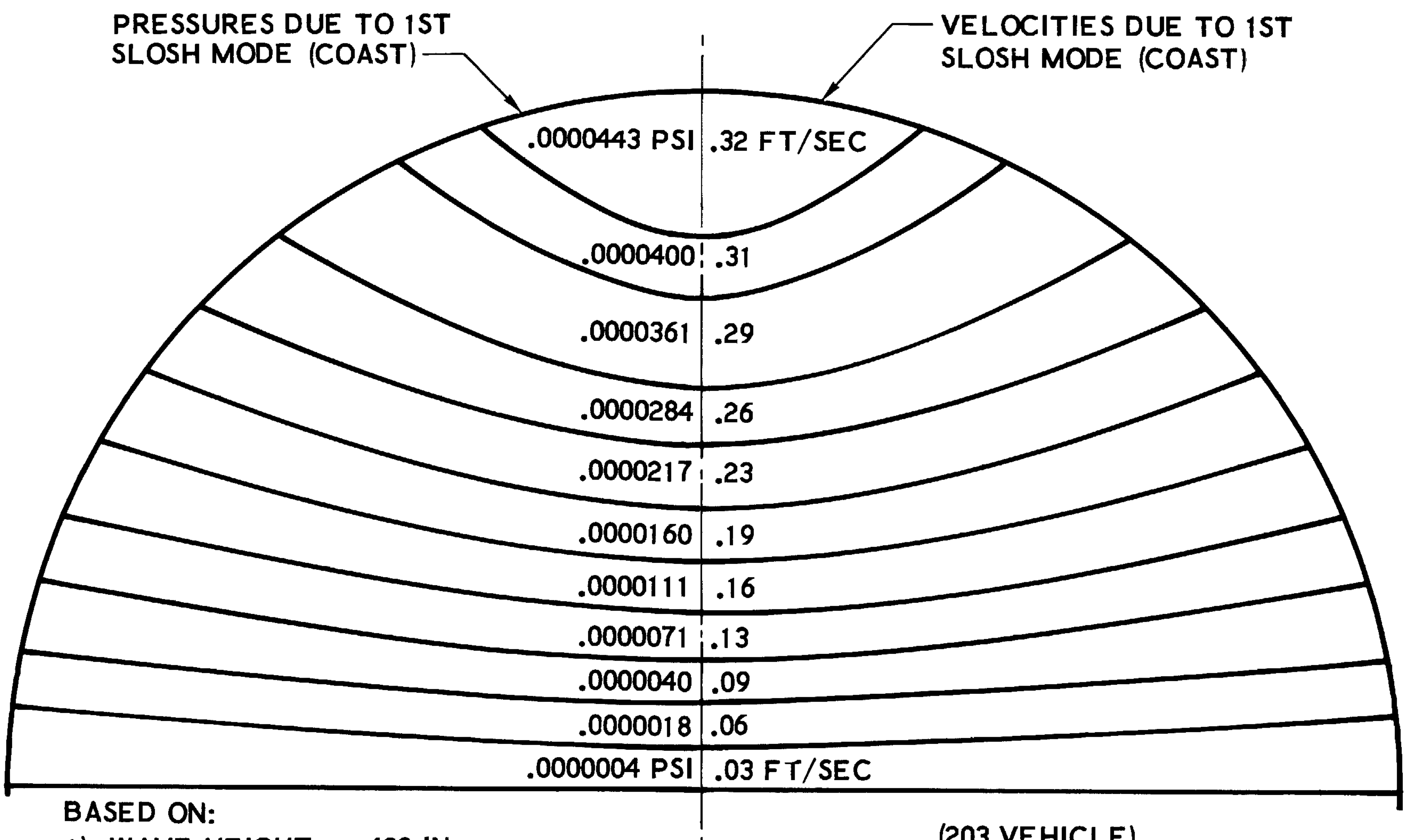


FIGURE 15

PRESSURES AND VELOCITIES DUE TO 1ST SLOSH MODE DURING THE COAST PERIOD



BASED ON:
1) WAVE HEIGHT = 400 IN.
2) FREQUENCY = 1.54×10^{-2} CPS

(203 VEHICLE)
(USE FOR SAT V)

FIGURE 16

small compared to this plot. Further analysis is required to more accurately predict the magnitude of second mode sloshing.

2.1.3.4 Baffle Design Support Data

To achieve full baffle effectiveness, the baffles must be located correctly with respect to the liquid surface. Dispersions in LH_2 level at cutoff arise from off-nominal vehicle performance parameters, manufacturing tolerances, propellant loading tolerance and fuel density perturbations. Since knowledge of the distribution of these functions is scant, their net effect on fluid level is presented in two ways: As a statistical quantity based on best estimates of parameter distribution, and as a worst case arithmetic sum the probability level of which is unknown. The results are as follows:

	Nominal Level (Station Number-inches)	Three Sigma Dispersion (inches)	Worst Case (inches)
SA-203	443	plus 6.4, minus 6.8	plus 10.6, minus 11.3
Saturn V	509.3	plus or minus 10.0	plus or minus 17

It should be noted that the nominal levels given above are based on current estimates of nominal vehicle and mission parameters. Based on past experience, it is expected that these parameters will change. Therefore, it should be emphasized that baffle placement must be considered as a factor whenever changes in these parameters are proposed. An additional 2-inch dispersion has been added to the three sigma dispersions to account for nominal performance changes. This results in a total uncertainty of $\pm$ 12 inches. For convience this same dispersion has been applied to 203. Therefore, for design considerations a total dispersion of plus or minus 12 inches about the nominal LH_2 cutoff level has been applied to SA-203 and Saturn V.

2.2 Diffusers

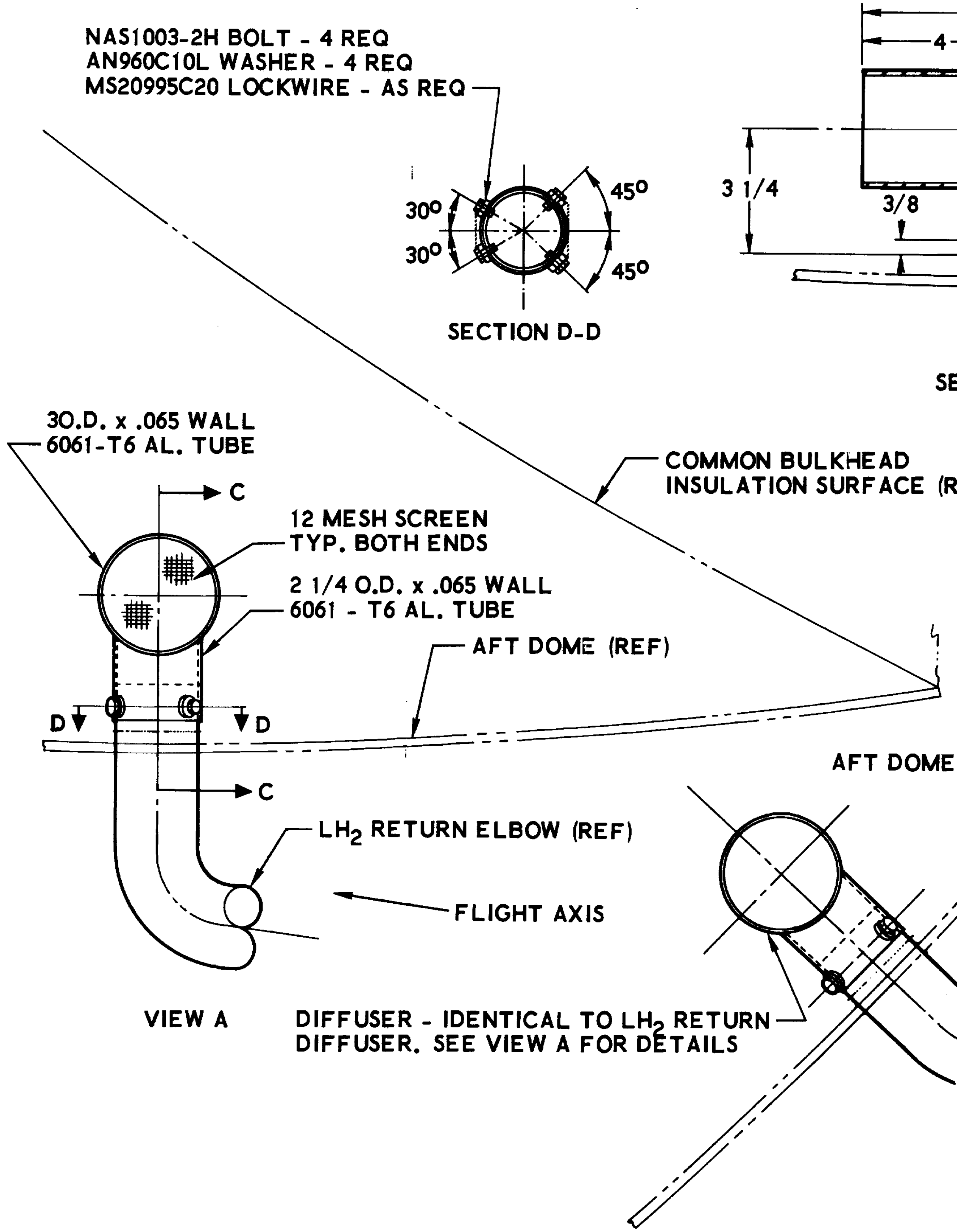
The recirculation return lines as well as the LOX and LH_2 feed lines may expel relatively high velocity liquid vapor flow into the tanks at certain operation modes during low g-level conditions. An adequate diffusion or diversion of the flow is required to prevent sloshing and/or geysering of the liquid into the forward domes. For this reason, the recirculation lines of both tanks have to be provided with diffusers and the screens of the LH_2 and LOX feed lines have to be modified to insure proper diffusion and diversion of the back-flow. The final design concepts, as well as the considerations involved, are presented in this section. Preliminary layouts of the diffusers are shown in Figures 17, 18 and 19.

2.2.1 Diffuser Design Considerations

2.2.1.1 Recirculation Return Lines

Both the LOX and LH_2 lines consist of 2" tubing. The maximum LOX cooldown flowrate is of the order 7 lbs/sec and the flow velocity is 5 ft/sec. The maximum LH_2 cooldown flowrate is of the order of 1.5 lbs/sec with a velocity of 17 ft/sec. Both velocities are large enough to penetrate the liquid bulk and create disturbance at the surface. It is not exactly known just how much diffusion is required to avoid surface disturbance. The most conservative approach yielded a maximum allowable vertical velocity component of 0.9 ft/sec on the hydrogen side and 0.4 ft/sec on the oxygen side. Although the LOX provides more velocity damping than LH_2, the short distance to the liquid surface does not permit much diffusion. However, this approach neglected the diffusive effect of the liquid shear forces.

Altogether, the comparison between the high actual return velocities and the tolerable low velocities makes it clear that diffusion alone does not represent a good solution to the task of avoiding surface sloshing,



NAS1003-2H BOLT - 4 REQ
AN960C10L WASHER - 4 REQ
MS20995C20 LOCKWIRE - AS REQ
30°
30°
45°
45°
SECTION D-D
3 1/4
3/8
30.D. x .065 WALL
6061-T6 AL. TUBE
COMMON BULKHEAD
INSULATION SURFACE (R
C
12 MESH SCREEN
TYP. BOTH ENDS
2 1/4 O.D. x .065 WALL
6061 - T6 AL. TUBE
AFT DOME (REF)
D
D
C
AFT DOME
LH2 RETURN ELBOW (REF)
FLIGHT AXIS
VIEW A
DIFFUSER - IDENTICAL TO LH2 RETURN
DIFFUSER. SEE VIEW A FOR DETAILS

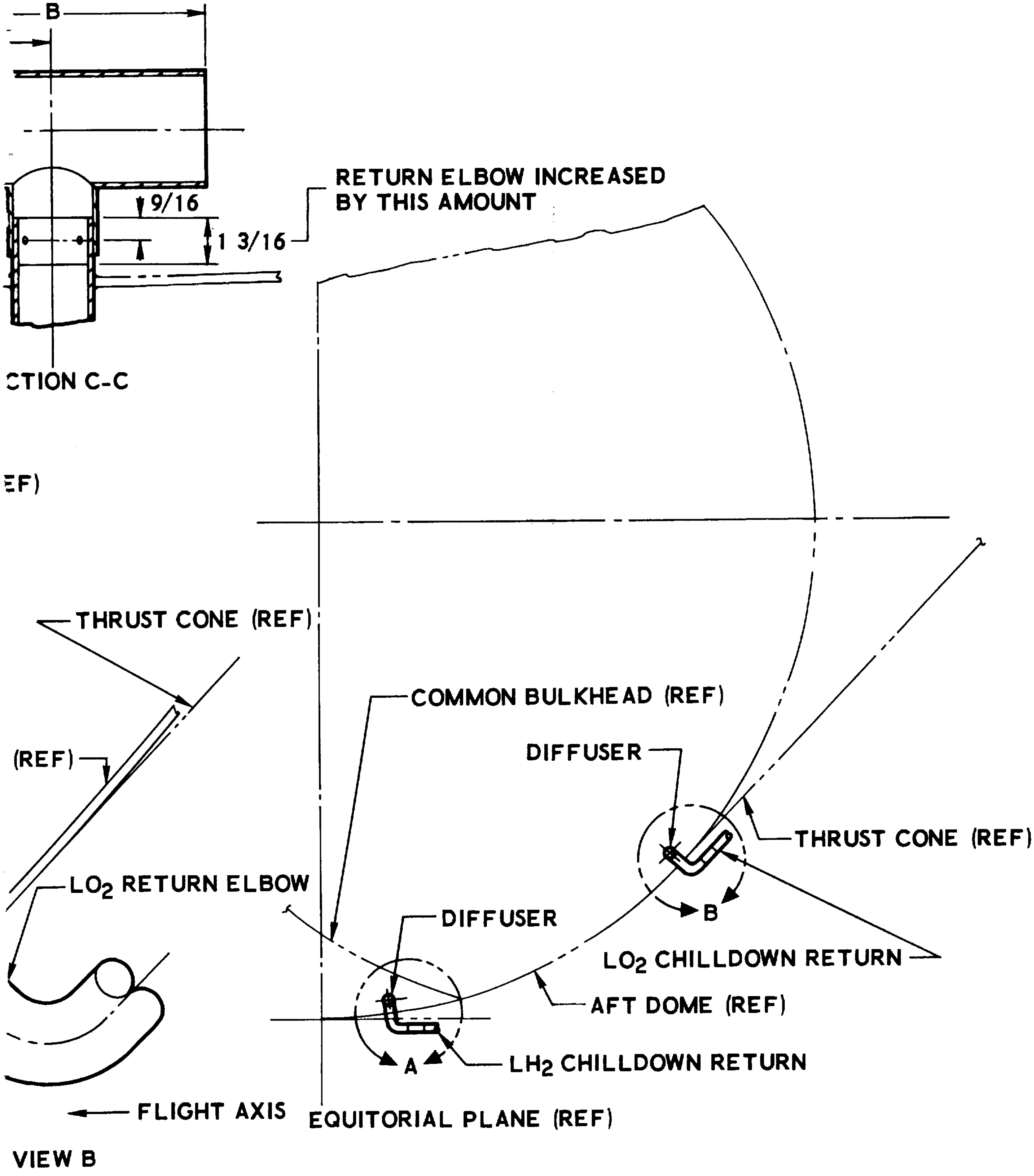


FIGURE 17 RETURN LINE DIFFUSERS, RECIRCULATING CHILL SYSTEM

LOX FEEDLINE DIFFUSER

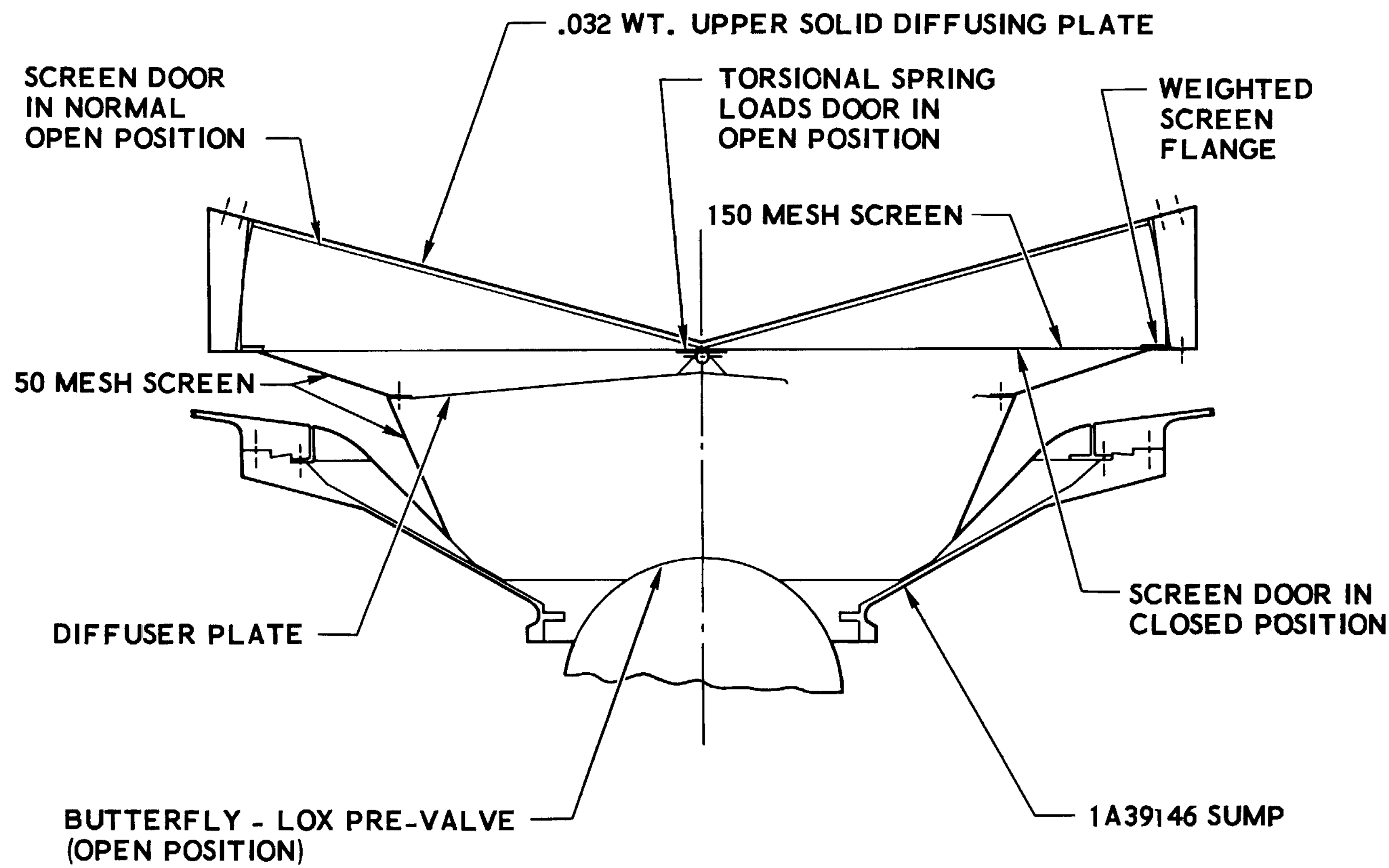
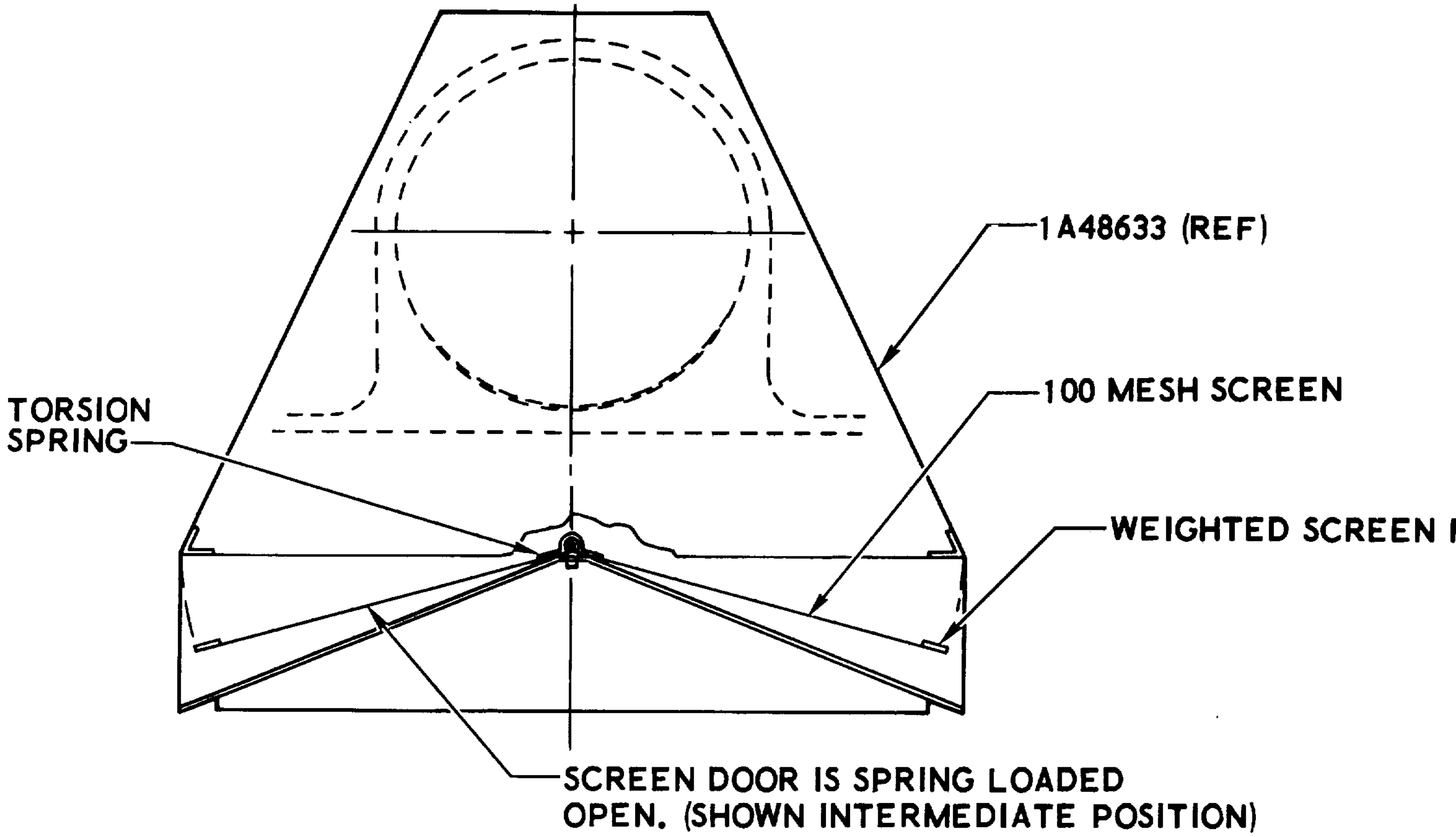
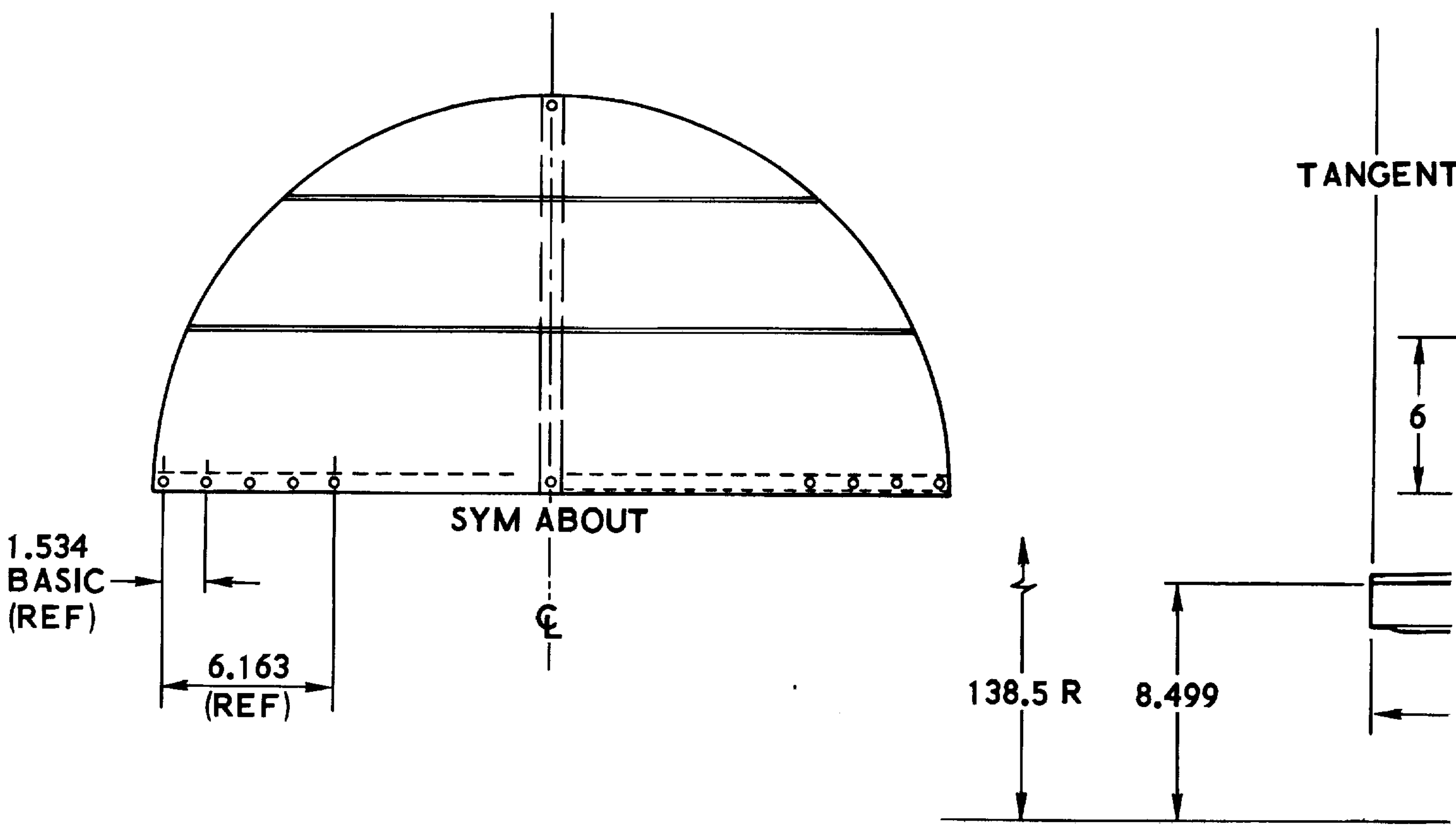


FIGURE 18



1A48633 (REF)
100 MESH SCREEN
TORSION SPRING
WEIGHTED SCREEN
SCREEN DOOR IS SPRING LOADED OPEN. (SHOWN INTERMEDIATE POSITION)



TANGENT
6
SYM ABOUT
℄
1.534 BASIC (REF)
6.163 (REF)
138.5 R
8.499

'LANGE

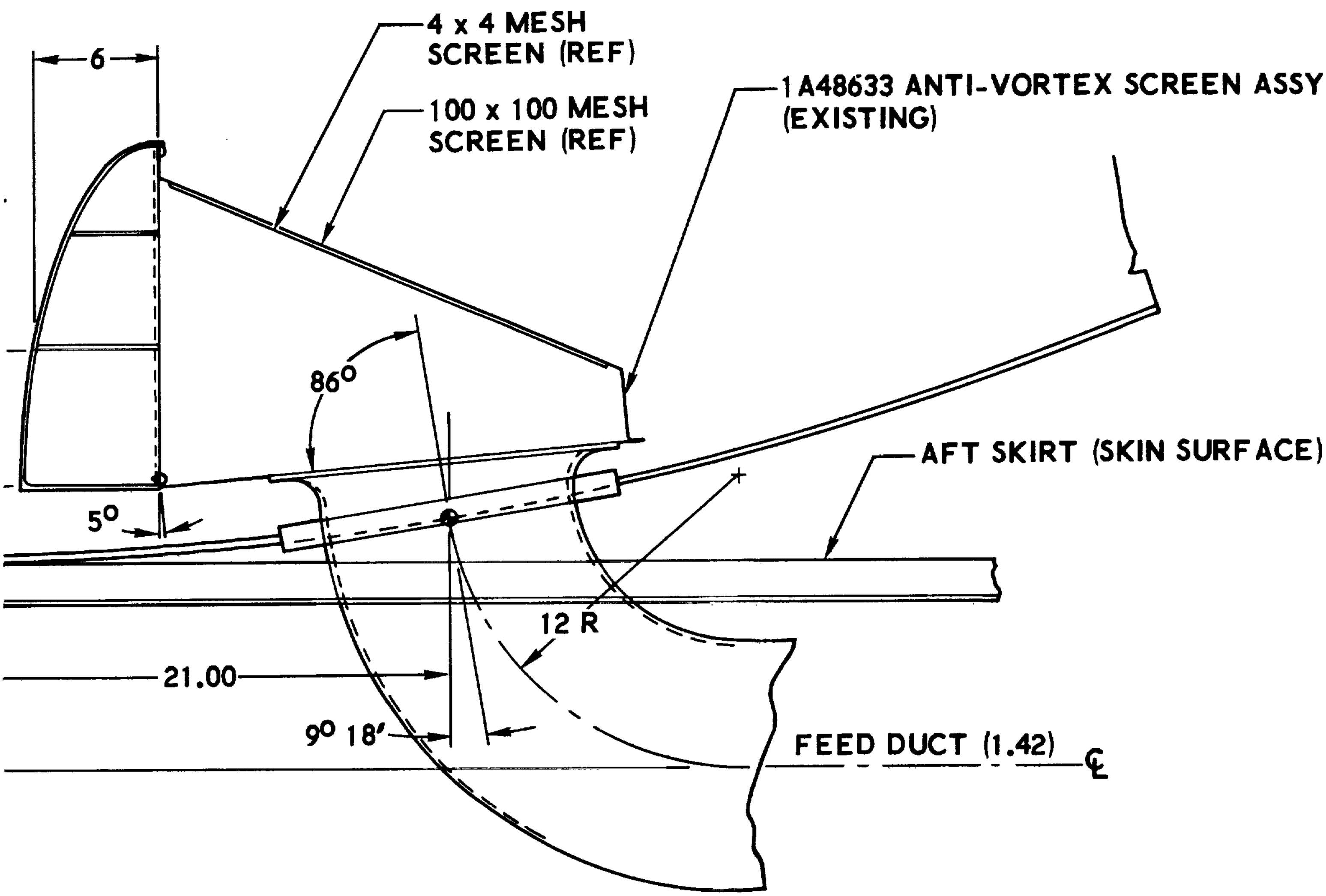


FIGURE 19 LH$_2$ ANTI-VORTEX TOP

since a weight penalty would be involved. Thus, a diversion of the flow into the horizontal plane becomes mandatory.

2.2.1.2 LOX and LH_2 Feed Lines

The existing screens at the inlet of the LOX and LH_2 feed lines have demonstrated their anti-vortex and filtration capability on several S-IVB Battleship tests as well as on many S-IV hot firings. However, during low "g" operation modes, two additional design requirements are essential.

The first requirement is a design which prevents bubbles from being trapped inside the screens during the restart sequence. At the latter part of the chilldown period the pre-valves are being opened, thus allowing the chilldown flow to return to both tanks by a shortcut through the feedlines and the screens. Due to the large feedline diameter, the flow velocity is extremely low and the danger exists that the gas bubbles might not pass through the screens. This condition would imperil the engine restart and has to be avoided.

The second design requirement is thecapability of the screens to adequately diffuse or divert backflow created at engine cutoff. During Battleship firings, pressure spikes were experienced after engine cutoff. They were recorded at the engine interface (pump inlet) as well as in the chilldown lines close to the prevalve. While the pressure spike in the LH_2 feed line is of short duration, below 0.2 seconds, the pressure spike in the LOX feed line lasts for more than 1 second. The magnitude of the pressure spike is ofthe order of 16 psi at the LOX as well as the fuel pump inlets. The spike has decreased to a 4-6 psi differential by the time it reaches the LOX and fuel chilldown lines, due to the damping effect of the lines and bellows, as well as the fluid in between Based on these measurements an analysis has been carried out to determine backflow velocities. The results indicate that at the feed line inlets the backflow velocity amounts to approximately 16 ft/sec in the LOX feed line and approximately 50 feet/sec in the LH_2 feed line. The conservatively estimated permissible vertical velocity component is the same as quoted for the recirculation return lines, i.e. 0.9 ft/sec at the LH_2 feed line connect and 0.4 ft/sec at the LOX feed line connect.

Any proposed change on both the LOX and the fuel screen, however, should not impair their filtration and anti-vortex capability. Any change should also maintain the present pressure drop across the screens.

2.2.2 Diffuser Design Approach

2.2.2.1 Recirculation Return Lines

Figure 20 shows five of the many diffuser concepts considered. All of them attempt to divert the flow into the horizontal direction and to diffuse to an area ratio of 4.5.1. The sketches are done at the same scale so that the sizes can be compared. The concepts, "a", "b", and "c" do not incorporate screens, the concepts "d" and "e" do. For this reason, "b" and "c" turn out to be rather large, thus generating support problems. "a" is a plenum design. The use of screens was met with some reserve initially. However, it is felt that the velocities are high enough to prevent the trapping of bubbles. The concepts "d", "e" and "a" are under close consideration with preference for "d" because of its simplicity.

2.2.2.2 Feed Lines

The present LOX screen would diffuse the backflow to a downstream velocity of 2.5 ft/sec. This is not considered to be low enough compared with the allowable vertical velocity component of .4 ft/sec (see para. 2.2.1.2). However, a diffusion to velocities of the order of 1 ft/sec would require a very large screen surface with a complex support structure. There exist difficulties of securing such a structure with the present fittings and the weight penalty would be appreciable.

The present LH_2 screen would diffuse the backflow entering at 50 ft/sec to about 5 ft/sec according to its surface area. In reality, however, the geometry of the screen together with the tank geometry at the feed line connect is thus that very little diffusion can be achieved no matter what surface dimensions the screen has been given. The flow will tend to pass the 9 inch distance between the feed line connection and the common bulkhead and will then be diverted up and to the sides by the slope of the bulkhead.

Therefore, for both the LOX and the LH_2 screens the present diffusion rate was considered the maximum to be achieved. The design effort was concentrated on alterations of the present screens with the aim of flow diversion and bubble trap prevention.

Bubble trap prevention requires a major change in the present screens. It will be achieved for each screen by altering the firmly connected lid into two hinged doors which will be opened during the critical cooldown phase. Two mechanisms for opening the doors were investigated. The first was a piston actuation system based on the pressure differential across the recirculation pump. However, it was feared that after the opening of the prevalves the pressure differential would drop off to too low a value to keep the doors open. The second mechanism is based on the balance between gravitational and spring forces. Under low "g" conditions the spring would overcome the gravitational force of the doors and the doors would open. Under high "g" conditions the gravitational forces of the door would overcome the spring force and keep the door closed. The latter approach has been chosen to be incorporated in the proposed redesign of the screens.

The flow diversion will be achieved with baffles above the vertical exit passages of the screen. They will be in a sufficient distance such that when the hinged doors come open, enough width will be available for the bubbles to pass. The doors will be stopped by the baffles.

2.2.2.3 Summary

The selected diffuser for the recirculation return line is the short tee with the screened exits, (version "d" on Figure 20). The decision was based on the simplicity of the hardware design and installation. It was felt that although an improvement of the present situation (no diffusers at all) is necessary, no chance should be taken of causing structural problems which might require extensive testing. The short tee is both simple and compact.

The selected screens for the LOX and LH_2 feed lines are basically the ones which have been in use already. They will be subject to the modifications discussed in section 2.2.2.2; that is, the incorporation of hinged doors and the addition of baffles. Alternative designs, although under close consideration, were ruled out during the earlier part of the investigation. It was felt that the present screens have performed satisfactorily in their basic function which is the anti-vortex and filtration capability and that their rate of diffusion is quite good if their dimensions are taken into consideration. The only choice to be made was in the selection of the mechanism to open the doors where the spring mechanism seemed to be a simpler one in design and installation.

2.2.3 Diffuser Design Requirements

The diffusers proposed for the recirculation lines are tee joints with screens on each end, (version "d" in Figure 20). The proposed modification of the present LOX and LH_2 screens at the feedline connect includes hinged lids and the addition of flow diversion plates.

2.2.3.1 Recirculation Return Lines

The final design requirements established for both the LOX and the LH_2 recirculation lines are to provide a diffusion at an area ratio of about 4.5.1 and a version of the flow into a horizontal plane. Pressure recovery is not

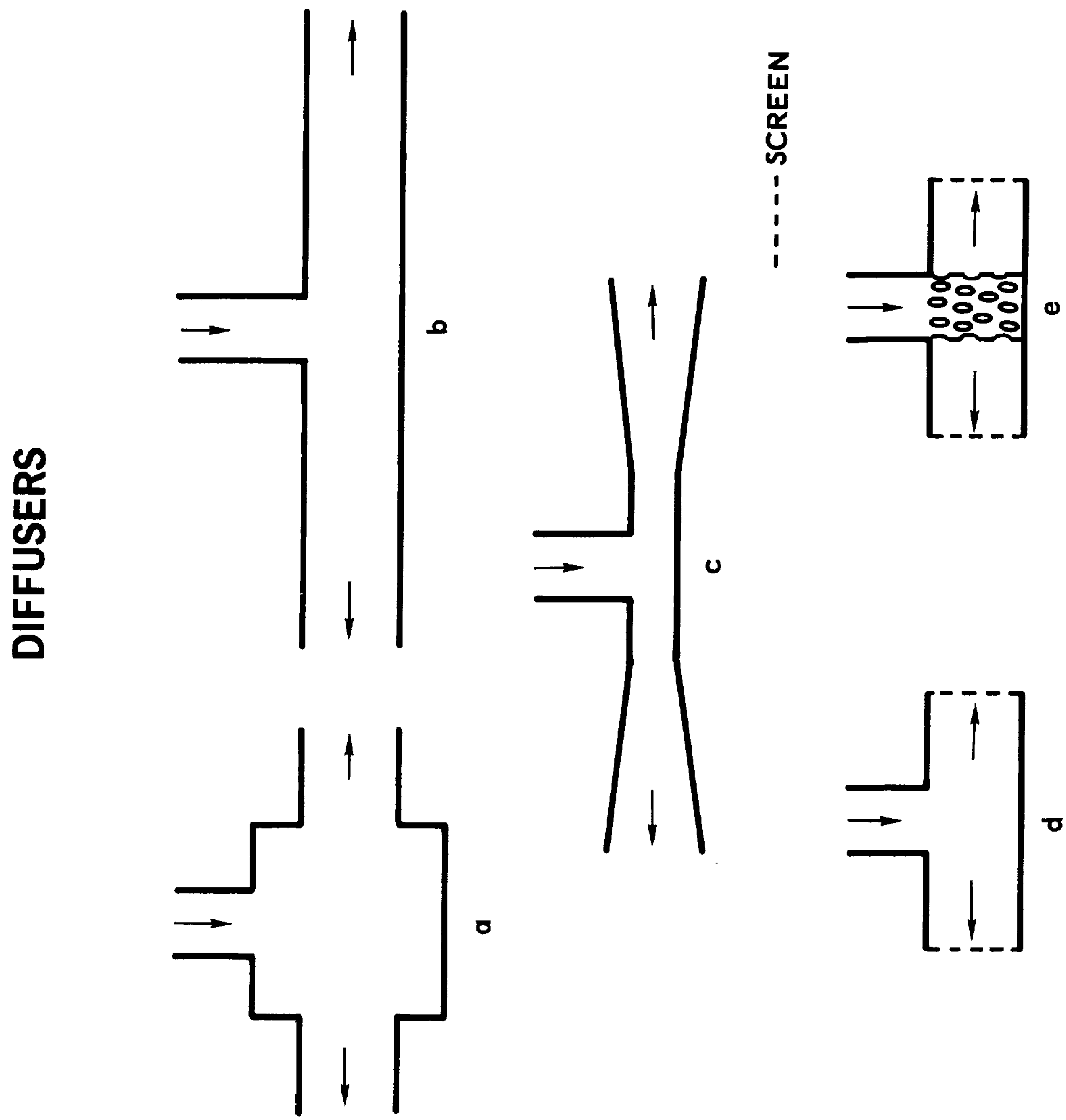


FIGURE 20

essential. The expected loads during the cooldown period are small and of the order 1 to 2 lbs. (There might be a somewhat higher load immediately after engine cutoff due to the opening of the LOX and fuel bleed valves, which would expose the diffusers to the decaying pressures downstream of the pumps. This condition, although not considered to be serious, remains to be investigated). The screens should have a 12 to 16 mesh per inch.

2.2.3.2 LOX and LH_2 Feed Lines

The LH_2 screen doors should create a passage large enough to pass a spherical bubble of a 6" diameter. The baffle above the screen lid should extend toward the common bulkhead to block the vertical passage between the screen and the common bulkhead. Screen meshes, rate of diffusion, and ΔP remain unchanged.

The LOX screen doors should create a passage large enough to pass a spherical bubble of a 4" diameter. Any change in screen meshes should not alter the screen ΔP. The rate of diffusion shall not be decreased.

The expected loads on the fuel and the LOX screens are of the order of 200 lbs. each. However, a pressure wave passing at sound velocity could possibly exert an instantaneous load higher than this on the screens. The spring constant on the hinged doors remains to be defined.

2.3 Liquid-Vapor Separator

Movement of droplets of liquid in the ullage during low gravity conditions is significantly influenced by the movement of gas in the ullage. This is especially true in the vicinity of the vent entrance where the flowing gas entrains the liquid globules and vents them overboard. If the amount of entrained liquid is large, a serious loss of propellant can result. The amount of entrainment is difficult to predict and the magnitude of the problem will not be known until the 203 experiment results are examined.

The proposed solution to the separator problem is that of reducing the amount of liquid entering the vent rather than the more common idea of removing liquid after it has entered the vent. A long tube or standpipe extending to the region in the ullage of minimum liquid entrainment will reduce the loss of unvaporized hydrogen. This solution is satisfactory only if the problem of slosh and entrainment are mild.

Severe and persistent slosh and high liquid quality ullage will necessitate the employment of an externally powered separator.

The Pesco centrifugal separator, which was originally planned for use on the S-IVB, could be modified to be driven by an electric motor. This type of modification would probably involve the least development time for a dynamic separator. However, the installation of a dynamic separator would result in additional complexity and weight penalty. A preliminary layout of the proposed solution to the separator problem is shown in Figure 21.

2.3.1 Design Considerations

Low gravity phenomena and practical design restrictions influence the design of the separator system. The primary factor to be kept in mind is that body forces due to gravity or acceleration are almost completely absent. Some separation takes place due to density difference, but the process is very slow.

The slosh phenomena presents a very severe demand to any separator. The slosh wave can introduce pure liquid into the separator thus providing no basis of discrimination to the device. Liquid will surely be vented if slosh is severe enough to periodically submerge the vent. The same consideration holds for the case of excessive liquid level rise. This phenomena is the result of bubbles forming in the bulk faster than they can rise to the surface and is commonly called "boil over."

Entrainment must be examined both from the standpoint of liquid quality and droplet size. High liquid quality and small droplet size each make for difficult separation. Very little is known about entrainment in low gravity, but it is hoped that the 203 liquid hydrogen experiment will provide answers.

Rate of gas generation, or boil off, is important. A given separator is most efficient at the design flowrate. High flowrates can give poor separation

CONTINUOUS VENT SYSTEM STANDPIPE

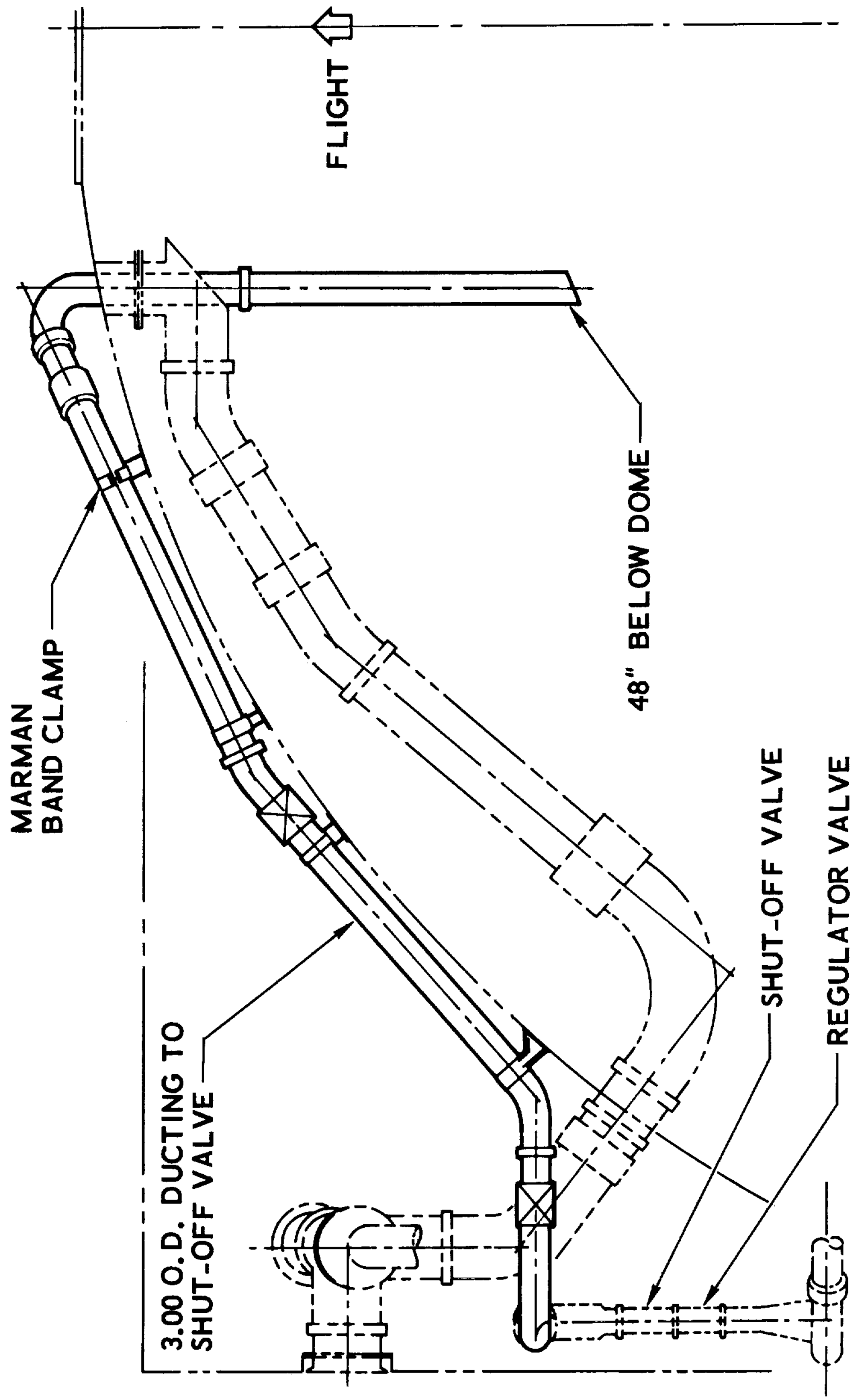


FIGURE 21

efficiency and possibly prohibitive pressure loss. Low flowrate can also give poor efficiency. Fortunately, the flowrate during continuous venting is reasonably constant for most of the vent period.

Pressure drop must be considered for all vent conditions including filling. Powered separators require a power source that may overtax the vehicle supply. Separators that require moving parts or elaborate controls must be examined from the standpoint of complexity, reliability and development time. As usual, weight must be closely watched to insure that the separator does not weigh more than the liquid saved. DAC will continue investigating the desirability of using an electrical power separator.

2.3.2 Separator Design Approach

Several types of separators were considered in the study. It seems to be a relatively simple task to remove entrained liquid droplets from the gas that is being vented. Under very low gravity conditions, however, the liquid cannot be made to leave the separator under the influence of gravity. The Bond number in a static separator or liquid collector will be very low, indicating that surface tension forces dominate over the body or gravity forces. It is thus essential that one of the following is implemented.

a. The separator be made large so that all separated liquid can be stored until restart.

b. Mechanical means be provided to remove the liquid from the separator and return it to the tank.

c. A rotating centrifugal type separator be employed that separates and ejects liquid in one operation.

The various types of separators examined are described below.

2.3.2.1 Centrifugal

The centrifugal separators can be divided into three types; 1) self powered rotating, 2) externally powered rotating, 3) cyclone. The self powered rotating type uses a turbine, driven by the vented gas, coupled to the separator rotor. Lack of external power makes it attractive, but there is insufficient gas energy at high liquid qualities for effective separation. The externally powered (electric motor, hydraulic motor, etc.) would provide very effective separation over wide ranges of flowrates, but at the expense of power.

Pesco Products Division, Borg-Warner Corporation (per telephone conversation, Messrs. Nesbett and DiStefano to DAC personnel 26 March 1965) proposes to remove the Turbine from their liquid-vapor separator and replace it with an electric motor, probably identical to the S-IVB fuel chill-down pump motor. Weight of the unit was estimated to be 25 lbs. It would give 80% separation efficiency at 90% inlet liquid quality with a power requirement of 0.9 hp. DAC estimates that 165 lbs of battery would be required along with 27 lbs of miscellaneous electrical equipment for a total, including separator, of 217 lbs.

The cyclone type separates liquid by centrifugal force, but has no provision for removing liquid to the tank without the use of a pump.

2.3.2.2 Baffles

The baffle or "chevron" type relies on the inertia of the liquid globules. The gas-liquid mixture is forced to make drastic changes of direction around baffles placed in the flow. The gas turns, most of the liquid does not and impinges on the baffle. Under low gravity conditions auxiliary means must be provided to pump the liquid back to the tank. The baffle type is relatively simple and straight forward and should require only moderate development time.

2.3.2.3 Surface Tension

Basically similar to the baffle concept, the surface tension or "packed bed" device relies on impact of the liquid globules with the fiberous packing. The scale is such that surface tension causes the droplets to adhere and gradually migrate to the separator walls where a pump is required to remove the liquid and return it to the tank.

A fine-mesh screen stretched across the diameter of the tank acts much the same as fiberous packing. The tank wall corresponds with the separator wall, however, and the liquid thus has a path for return to the bulk.

2.3.2.4 Electric

The electric types include the phenomena of electrostatics (Cottrel separator) and dielectrophoresis. Both of these concepts appear to have merit, but the extreme development time associated with them puts their application some distance in the future.

2.3.2.5 Thermodynamic

Some thought was given to passing the vented liquid-gas mixture back through either; 1) the ullage or, 2) the bulk. To work, the boiling of the liquid in the vent line would have to; 1) condense some ullage gas or, 2) sub-cool the bulk. Many practical problems are envisioned with long lead time.

2.3.2.6 Standpipe

The region of minimum liquid globule generation is at the center of the liquid surface. Most of the boiling and free convection disturbances are localized at the walls. Maximum liquid velocities in slosh for both first and second mode occur at points away from the center of the tank. A long tube or standpipe from the top of the tank to a point a short distance above the liquid would therefore be in the most favorable position for minimum liquid loss (see Table I).

2.3.2.7 Summary and Recommendations

The various separator types are compared in Table II. All of the separators considered have long development times associated with them except for the standpipe and modified Pesco centrifugal separator. While the standpipe is not a true separator, it can reduce liquid entrainment and be installed with a minimum development time. It appears capable of reducing the amount of liquid vented especially if slosh and entrainment are not too severe. The weight penalty is relatively low. It is thus recommended that the standpipe be used on vehicle 203.

Cryogenic centrifugal separators have been the subject of intensive development. Adapting an electric motor to an already developed separator could reduce lead time to the point where such a system could possibly be installed as early as the 203 vehicle.

2.3.3 Design Requirements

Retrofitting the standpipe system will require the addition of another port in the tank wall. Provision must be made for venting during fill and ground hold. The present standpipe cannot be used since it will be submerged. The current vent outlet will thus be used for ground venting and the second port added through the old separator attach pad. Exterior plumbing will be rearranged so that the standpipe vents through the continuous vent system and the ground vent through the vent and relief valve.

Current plans are for a standpipe extending four feet from the top of the tank for S-V and a dimension to be determined for S-IVB-203.

TABLE I

A standpipe length of 4 feet is recommended based on the following.

Nominal Liquid Level Saturn V	533
Plus Increment for Maximum Level	18
Plus Increment for Maximum Rise Due to Boiling (Nominal + 12)	54
Plus Possible Meniscus Height	24
Possible Liquid Level	629
Top of Tank	683
Distance Between Liquid Level and Top of Tank	54

The 48 inch standpipe thus has a six inch margin.

COMPARISON OF SEPARATOR TYPES

TYPE	PROJECTED EFFECTIVENESS	EXTERNAL POWER REQUIRED	WEIGHT	DEVELOPMENT TIRE
Centrifugal				
Self Powered	Good	None	Medium	Long
External Powered	Excellent	Drive Separator	Heavy	Long *
Cyclone	Good	Return Liquid	Medium	Medium
Baffle	Good	Return Liquid	Medium	Medium
Surface Tension	Good	Return Liquid	Medium	Medium
Electric	Good	Return Liquid	?	Long
Thermodynamic	?	None ?	Heavy	Long
Standpipe	Fair	None	Light	Short

* Assumes no prior development

2.4 Studies of Propellant Motion

The LH_2 tank slosh suppression devices discussed in Section 2.1, while apparently satisfactory, are based on preliminary studies of fluid behavior under very low acceleration. Further analysis effort is required to assure design adequacy. These studies should be directed towards the following three areas. The further development of a low acceleration slosh model, studies of LOX sloshing motion and studies of coupling between the APS coast slosh coupling. The study approach proposed in these areas is described in the following paragraphs.

2.4.1 Low Acceleration Slosh Model

Under very low acceleration conditions the dynamic model used for present slosh analysis will not be adequate for all conditions. For low sloshing amplitudes it is felt that the present model is adequate although further study is indicated to verify this. However, particularly for high amplitude slosh at low acceleration levels the basic model is considered inadequate because of several phenomena. Fluid particles, at some distance above the nominal level with a slosh acceleration greater than the vehicles static acceleration, are restrained by surface tension only. If the surface tension forces are small, with respect to the acceleration forces, the fluid particles will break away. This wave break-up should occur almost as soon as the fluid goes into tension at normal acceleration levels. A limit can thereby be imposed on the upper limit of slosh waves. However, at acceleration levels approaching 10^{-5} g's, the surface tension will be able to support a proportionally larger volume of fluid. The break-up amplitude will thereby be increased.

The effectiveness of the baffles can be changed because of the presence of a large meniscus and of bubbles in the boundary layer.

A study will be made to determine a dynamic slosh model which is adequate for the environment of the S-IVB. This study will rely primarily on work done by other agencies, including NASA/MSFC, NASA, Lewis, and Dr. Satterly at Stanford University.

This study will be supported by scale model slosh testing at normal gravity. This model testing will be required to support analysis in the low acceleration and high slosh amplitude regions. This testing should be performed on the LOX tank as well as the LH_2 tank. Specifically the testing will be carried out to determine the sloshing transfer functions at low bond numbers. These would include natural frequencies, displacements and damping for first and second mode sloshing. The models will be small (around two inches in diameter). The construction material will probably be glass with water as a sloshing medium. The models will be mounted to a lateral excitation device. A strain gage balance will provide for measurement of sloshing forces. High speed color cameras will provide visual coverage of the fluid response. Frequency and excitation magnitude shall be varied to determine the fluid mass, damping and spring properties. More than one set of scale factors will be used. Thus, the scaling laws can be verified for the particular tests in question. The variance in scaling factors will necessitate the construction of more than one model. However, the sloshing medium may also be changed to determine some points on the trend curves.

This study will be supported by scale model slosh testing. This will include testing at one g of a model which is dynamically scaled to the correct bond number. Using this model the dynamic transfer function of the sloshing medium will be determined as a function of fluid height. This would include frequencies, displacements, and damping for first and second mode sloshing. A frequency check of the scaled model would probably be sufficient, also to verify the model used for low amplitude sloshing.

Further verification can be obtained in conjunction with the drop tower tests which are planned at NASA/MSFC.

A further inadequacy of low acceleration sloshing model is the low sloshing velocity which results. These velocities may be as low as the convection velocities associated with thermal gradients in the fluid. Low Reynolds Numbers associated with the low velocities preclude the use of the usual formulas to predict baffle damping. Some difficulty may be encountered in evaluating the boost baffles for coast applications. Analytic effort will have to be expended to derive baffle formulas for these low Reynolds Number conditions. Possibly, correction factors can be applied to the existing baffle formulas. Due to Reynolds Number scaling problems, an adequate model to verify the above probably can not be made. No testing is envisioned in this area.

The results of these studies of low acceleration sloshing phenomena will be used in the study of APS coast slosh coupling discussed in Section 2.4.3.

2.4.2 LOX Motion at Cutoff

Because of the problems encountered with LH_2 sloshing at cutoff it is proposed that the behavior of the LOX at cutoff be investigated in a similar manner. To determine this behavior the first step will be to simulate the vehicle (SA-203, and SA-501) to determine the amount of LOX slosh disturbances that exist at shutdown. Shutdown for vehicle 203 is the end of flight and for vehicle 501 the beginning of orbital coast.

The effects which will be considered will be distrubances just before or at separation and distrubances caused by vehicle limit cycle during boost.

The vehicle model to be used for this study, consists of the "rigid body" with first and second mode LH_2 and LOX slosh masses, and a thrust vector control loop with gimball friction. Since gimball friction forces vary over a large range, it will be parameterized. The autopilot gains will also be parameterized to cover future changes and possible slosh corrections.

The study results will consist of:

a. Predicted specific LOX slosh disturbances at shutdown for the -203 and -501 vehicle
b. Parameterization to cover stage tolerances
c. Qualitative observations regarding the validity of the above results, and constructive suggestions of how autopilot gain, shaping, or any other parameter may be controlled to minimize slosh at shutdown.

Liquid oxygen sloshing, present at shutdown, can be amplified due to the transition from main engine thrust to coast thrust. The amplification factor is computed in the same fashion as for LH_2, viz. The maximum amplification is equal to the square root of the ratio of boost thrust to constant vent thrust. With the cutoff slosh amplitude known, the maximum slosh amplitude during coast can be computed.

The maximum slosh amplitude will probably be attenuated somewhat if the ullage thrust duration is timed to minimize hydrogen coast sloshing. The fact that the hydrogen and oxygen slosh frequencies are not exactly equal prevents the ullage time for minimum hydrogen momentum to also be the minimum for oxygen momentum.

Studies are proposed to investigate the LOX for maximum wave heights and shapes. The present baffles will play a significant role in this investigation. The possibility of using the 203 ring baffle in the Saturn V missions will also be considered. The results of these studies will determine the need for additional slosh suppression devices and/or liquid-vapor separators in the LOX tank.

2.4.3 APS - Coast Slosh Coupling

During coast vehicle attitude control is maintained by means of a pulse modulated on-off attitude control system. Basically, the operation of this system consists of sensing an attitude deviation from the desired attitude and attitude rate and then pulsing the appropriate APS engine to reduce this deviation to within acceptable limits. Two of the forces with which the APS must contend while providing attitude control are the forces resulting from LH_2 motion and LOX motion. Unfortunately, in contending with these forces and in maintaining vehicle attitude, it is possible for the APS to supply energy to either or both of the slosh motions and, consequently, to induce large slosh amplitudes. These large slosh amplitudes may result in the venting of liquid or in excessive APS firings. The venting of liquid is harmful because of the loss of propellants and also because of the possibility of inducing large disturbing moments which will result in additional APS propellant usage. It is the purpose of this portion of the study to detect any possible problems connected with coast attitude control system operation and LH_2 and LOX slosh motion.

The effects of coupling between coast attitude control system operation and LH_2 and LOX sloshing motion will be investigated by means of a multi-degree-of-freedom analog simulation. This simulation will include first and second mode LH_2 and LOX sloshing. Other effects which it is planned to include during the course of the study are the addition of the non-linear sloshing model including damping characteristics which were discussed in Section 2.4.1.

The study is expected to yield propellant motion time histories for various sets of initial conditions and parameter values. These histories will be analyzed to determine any possible problems resulting from APS - slosh interaction, the possibility of venting liquid, and the affect of sloshing on APS operation, propellant consumption, and engine duty cycle requirements. It should be noted that because of the random nature of many of the disturbance inputs, the results obtained should be treated as statistical quantities. A portion of the study, therefore, will be to obtain expected distribution of these parameters during coast flight.

Should any potential problems be uncovered, possible solutions will be investigated so as to insure satisfactory mission completion. These solutions may involve vent system changes, baffle redesign, or attitude control system gain changes.

In the area of attitude control system changes, there are two possible approaches. One is the use of the attitude control system as an active control system to control and suppress sloshing. The other is to design the attitude control system in such a manner that its operation does not excite large amplitude sloshing.

The first, and possibly most difficult, requirement of the active approach is for sensors which would detect the magnitude and direction of propellant sloshing. These could consist of an array of point sensors, additional mass probes, or some other device. The next requirement would be the development of control system logic which would suppress slosh without harmfully degrading APS duty cycle, fuel consumption, or attitude control mode requirements.

The possibility of changing attitude control system parameters such as minimum impulse size or control logic so as to minimize slosh excitation will also be studied. The analysis should indicate the effectiveness of slosh suppression as well as the effect of any changes on normal APS functions.

2.5 Backup Systems

The success of the S-IVB continuous vent system depends to a large extent on its propellant control capability. Serious doubts in regard to this capability have been raised (see previous sections). DAC has been asked to recommend for study alternate orbital venting systems which could be applied to the first Saturn 5 stages if these doubts are verified by the Saturn 203 orbital experiment, Centaur flight data, or other means. Proposed study outlines for three backup concepts are presented here.

These proposals are based on the following considerations:

a. The backup system should be available for the Saturn 501 mission with little or no schedule shippage.

b. The system should be in the form of a kit which could be added to S-IVB/501 and subsequent stages if and when the requirement for such addition is established.

c. Proven concepts and hardward should be used.

2.5.1 Cyclic Venting

2.5.1.1 Introduction

It is proposed that the problems and systems described in Section 2.5.1.4 be studied by DAC in regard to feasibility, reliability, payload degradation, cost, and schedule impact. The objective is to recommend a cyclic vent system--optimized in regard to these variables--for use as a backup to the continuous venting system on Saturn 501 and subsequent missions in the event that the continuous venting concept proves inadequate.

A return to the cyclic mode of fuel tank venting appears to be a feasible alternative to the present continuous venting scheme. Extensive development work would be necessary to overcome problems that contributed to discarding of the original subsystem and considerable redesign of the stage would be required in order to provide capability for adding a cyclic venting "kit" to early Saturn 5 stages. However, it is felt that this could be accomplished without unacceptable schedule slippage if work is begun immediately.

2.5.1.2 System Description

The cyclic venting concept is based on venting of the propellant tanks only upon demand. During most of the orbital coast period the tank vent valves are closed and no attempt is made to control propellant orientation.

When the fuel tank pressure rises to a certain level, a vent cycle is initiated by a pressure switch. The propellants are first settled at the aft ends of the tanks by means of ullage rockets. The vent valve is then opened pneumatically for a fixed amount of time and the tank is blown down through propulsive nozzles (which permit shutdown of the ullage engines at the beginning of blowdown). It may also be necessary to allow the LOX tank to initiate vent cycles in which both tanks are vented.

Just prior to restart the propellants are settled using the ullage rockets and the fuel tank is blown down and repressurized with helium in order to meet NPSH requirements.

2.5.1.3 Problems Associated with the Cyclic Venting Mode

Although system weight was a major consideration in the switch from cyclic to continuous venting, the decision was also influenced by several conceptual problems associated with cyclic venting.

2.5.1.3.1 Ullaging Capabilities

Both the adequacy of the ullaging system design and the ability of the Tapco ullage engines to perform in accordance with the design were in question at the time the cyclic system was dropped.

Detailed analysis of fuel tank internal thermodynamics indicated that the required number of vent cycles might be larger than that for which ullaging propellants had initially been provided. Also, analysis of settling procedures indicated that a cycle might require longer ullage rocket burning than the 32 seconds originally planned.

Meanwhile, the Tapco engine development program was running into trouble in regard to meeting the steady-state burn requirements and providing the total burn time needed.

2.5.1.3.2 Entrainment

The cyclic venting concept included a mechanical separator intended to prevent propellant loss due to entrainment of liquid droplets during a blowdown under saturation conditions. At the time of the switch in systems, the chances of adequate separator performance appeared slim.

2.5.1.4 Study Areas for Revival of the Cyclic Venting Concept

This section presents description of study areas involved in determining the feasibility of and an optimum form for a cyclic venting backup system.

In order to provide backup cyclic venting capability for Saturn 501 and/or other early Saturn vehicles, it will be necessary to solve the problems described in 2.5.1.3 and to make provision for any required hardware changes as soon as possible. Concurrent hardware development may be necessary in areas where the cyclic system differs from the continuous vent system and also in areas where the solution to the problems posed above cannot be readily determined.

2.5.1.4.1 Ullaging Requirements

2.5.1.4.1.1 Required Number of Cycles

The number of vent cycles required is a key factor in regard to hardward modifications. Excessive cycle requirements could necessitate major redesign of the aft skirt and of APS propellant supplies, and may be an obstacle to ullage engine development. The number of cycles must be determined and methods for reducing this number are being investigated.

2.5.1.4.1.2 Reduction of Number of Cycles by Mechanical Agitation

Predictions of large numbers of vent cycles in the old cyclic system were due largely to the possibility of having intense thermal gradients in the liquid hydrogen. The number of cycles could have been reduced from about 25 to three or four if complete thermal mixing could have been assured.

Results of a preliminary study have indicated that such mixing could be practically accomplished by means of small pumps immersed in the propellant. The weight of the pumping system, including power supply, is estimated to be on the order of 350 pounds. Since this is a lot less than potential savings in boiloff and APS weight, this concept is being examined in detail (see appendix A). There is some indication that the S-IVB chilldown pumps may be applicable to this system.

Propeller or other types of shaft-driven agitators may also provide a practical mixing system and studies are proceeding.

2.5.1.4.1.3 Reduction of Heat Input to Reduce Number of Cycles

Various methods of reducing propellant heating have been considered for possible use with a cyclic venting system. They are briefly described in Table 1 and are discussed below. Maximum estimated propellant heating quantities are also shown in the table.

These estimates can be used for rough evaluation of ullaging requirements to accomplish venting. Liberal use has been made of SM-46745 "Heat Transfer Dispersion Study on the S-IVB Liquid Hydrogen (LH_2) Tank" for determining the performance of the various systems discussed herein.

No. 1

This is the current system. The insulation consists of a 1-inch thickness of polyurethane foam on the cylindrical section and a 0.5-inch thickness on the forward dome. Data show that the conductivity of the insulation is 0.035 Btu/ft-hr-°F or less. (This value is conservative.) The tank cylinder exterior is painted white. The optical properties shown are those following simulated extra terrestrial solar radiation exposure.

No. 2a, 2b, 2c

These show that substantial propellant heating reductions may be attained by the fairly simple method of using external surface finishes having superior optical properties. The "best white paint" indicated is one which has been tested and has shown excellent optical properties both before and after simulated solar radiation. It appears to be satisfactory for use. The aluminum silicone paint has also been tested and appears to be satisfactory before and after simulated solar radiation. The aluminized mylar or aluminum foil systems would require development. Either of these would have to be in complete bond with the tank exterior throughout the mission. The bonding technique would have to be developed. Weather effects are significant at least for the mylar. It could be applied, however, a few weeks prior to launch for best performance

No. 3

Theoretical orientation is greatly limited in performance improvement because of the strong earth radiation influence irrespective of orientation. Communications and other problems may make this method unfeasible. It is, however, worthy of further consideration since the "problems" may not be very significant.

No. 4

The addition of external bulk insulation provides substantial potential reduction of propellant heating. Helium purge is not required. The external insulation is expected to have very good performance in orbit because of vacuum conditions.

No. 5

External bulk insulation with no internal insulation is a thermally superior system because of its low conductivity in a vacuum. It must be helium purged during ground hold.

No. 6

A high performance insulation system for the Saturn V/S-IVB LOR mission has been analyzed and shown to reduce the heat input (for the cyclic venting case) to approximately 200,000 Btu. Crinkled aluminized mylar (NRC-2) is applied to the cylindrical portion of the hydrogen tank. A jettisonable fiberglas shroud is used to protect the aluminized mylar from the aerodynamic environment during boost. During ground hold, a helium purge is used to prevent air condensation in the shroud/tank annulus. To protect the aluminized surfaces from overheating in orbit, a white coated ($\alpha = 0.3$, $\epsilon = 0.9$) bag is used as the external surface. There is no internal insulation in the LH_2 tank except in joint regions. The details of the Saturn V/S-IVB high performance insulation study are presented in SM-46554, dated January, 1964.

No. 7

This system is similar to that of No. 6 except that helium purge is not required.

No. 8

Subcooling would be accomplished continuously during ground hold. Good mixing in orbit would be required and may be the chief disadvantage.

The required level of subcooling (10°R) provides a heat sink for all of the propellant heating. The process is applicable to any of the systems shown in the table.

No. 9

The LH_2 can store an increase of roughly 300,000 Btu after first burn. This disregards NPSH requirements and the effects of venting at high LH_2 bulk temperatures (flash). Good mixing is required. It could result in venting at very infrequent intervals. It is applicable to any of the systems in the table. This is a device to provide infrequent venting, but is not necessarily superior since long duration venting may be required.

No. 10

The purpose is to develop a vapor barrier adjacent to the wall with liquid in the interior. Unknown fluid-screen behavior is involved.

No. 11

Same as No. 10.

Summation

Almost any degree of propellant heating reduction is attainable depending on complexity and development. Simplest methods produce up to 25 per cent reduction. Moderately complex methods can provide 50 per cent and highly complex methods from 75 to 100 per cent effect reduction.

CYCLIC VENTING PROPELLANT HEATING

No.	System	Effective	Absorptivity	Emissivity	Remarks	Total Q BTU
1	Present Insulation	0.035	0.4	0.9	Present white paint after ultra violet exposure	820,000
2a 2b 2c	Present Insulation	0.035	0.24	0.9	Best white paint aluminized silicone paint Aluminized Mylar or Al Foil	750,000 700,000 620,000

CYCLIC VENTING PROPELLANT HEATING (Continued)

No.	System	Effective	Absorptivity	Emissivity	Remarks	Total Q BTU
3	Inertial Orientation	0.035	0.25	0.25	Aluminized silicone paint present insulation	640,000
4a 4b	Present Insulation + S-II External Insualtion	0.008	0.4 0.25	0.9 0.25		460,000 400,000
5	S-II Insulation (Only)	.01	0.4	0.9	Local internal insulation may be required at heat shorts	520,000
6	HPI (Only)		0.3	0.9		210,000
7	HPI + Internal		0.3	0.9		200,000
8	Present Insulation + Subcool 10°		0.4	0.9	Present white paint good mixing	*See Text
9	Complete LH_2 Mixing	-	-	-	Good mixing See text	-
10	Tank Screen Place 1" from Wall	.012	0.4	0.9	Requires substantial development	570,000
11	Tank Screen Placed 2" From Wall	.008	0.4	0.9	Requires substantial development	460,000

2.5.1.4.1.4 Settling Procedures

The criteria initially used to determine times in cyclic systems have since been subject to considerable criticism. The criteria are being examined taking into account recent theoretical and experimental developments as well as engine availability. Both venting and restart cases are under investigation.

2.5.1.4.1.5 Oxidizer Tank Requirements

Oxidizer tank venting requirements have been investigated to determine methods for integrating LOX venting procedures with those for fuel venting. Applications of cycle-reduction systems discussed above to the LOX tank will be considered in order to minimize interference with fuel procedures.

2.5.1.4.2 Ullaging Systems

2.5.1.4.2.1 Engines

When settling procedures have been fixed, an engine compatible with the precedures (as well as with schedule requirements) must be selected. The following systems will be considered:

a. Gemini OMAS engine - The Gemini hypergolic OMAS engine, derated to 70-pound thrust, is presently planned for ullaging use on the S-IVB. Its ability to meet the increased requirements in the cyclic system is under investigation.

b. Tapco S-IVB attitude control engine - This 150-pound thrust engine was to be used for ullaging in the cyclic system. However, development problems were encountered in regard to long steady-state firing. Present knowledge of the sources of these problems indicates that they could be eliminated without excessive effort.

c. Solids - A review of available information on solid propellant engines currently in production has disclosed several such engines which would be applicable to the cyclic venting system. Since a pair of engines would be needed for each cycle, solids are probably practical only in the case where the number of cycles is limited by the methods described above. Preliminary weight estimates favor hypergolic engines by a small margin, but this disadvantage could easily be offset by advantages in regard to reliability, availability, and ease of installation. Solids would fit particularly well into the concept of a cyclic venting "kit" to add to the stage upon discovery of flaws in the continuous vent system.

2.5.1.4.2.2 Hardware

Because of long lead times involved, hardware problems related to the cyclic venting mode require immediate attention. Of particular importance are structural changes in the aft skirt for addition of solid engines or larger hypergolic systems and development of expanded hypergolic tankage if that type of engine is chosen. Production drawings from the old cyclic system may be applicable to the latter item, but development times will still be critical. Modification of the tank vent systems may also be necessary.

2.5.1.4.2.3 Procedures and Control Systems

The venting procedure in the cyclic system was well established, but modification described in 2.5.1.4.1 may lead to procedural revisions. Electrical system changes should be investigated to insure compatibility with other systems and to identify long lead time items.

2.5.1.4.3 Liquid-Vapor Separation

Although the Pesco centrifugal separator did not meet the stage requirements, the results obtained prior to its cancellation indicated that the concept of mechanical separation has considerable merit. It is, therefore, recommended for consideration here.

Also recommended for study are:

a. Static separators (screens, baffles, etc.) coupled with capillary methods for collection of separated liquid.

b. A heat exchanger system which would reduce the temperature of any liquid entering the vent by expansion to low pressure and then use this cold liquid to cool the bulk by allowing it to vaporize by absorbing heat from the bulk (thus, reducing future boiloff by approximately the amount of liquid vented in the case where good thermal mixing exists).

c. Avoidance of rapid blowdown under saturated conditions. Saturated blowdown will probably be necessary in the cyclic system, but DAC one g tests have indicated that entrainment can be held to a minimum by limiting the rate of pressure reduction. Weight tradeoffs between entrainment losses and APS requirements for slow blowdown should be investigated.

Most of the above separation systems involve long lead time items which should be investigated from a schedules standpoint.

2.5.1.5 Study Outline

a. Investigate ullaging requirements

1). Number of cycles required

a). Reduction of number of cycles by mechanical mixing

b). Reduction of number of cycles by reducing heat input (paint, insulation, etc.)

2). Settling time versus thrust

a). For venting

b). For restart

3). Integration of LOX tank procedures

b. Investigate ullaging systems

1). Engine availability and applicability

a). Hypergolics

b). Solids

2). Hardware modifications

a). Aft skirt

b). Hypergolic tankage

c). Vent hardware

d). Concurrent development requirements

3). Procedures and control systems

c. Investigate liquid-vapor separation

1). Separators

a). Mechanical

b). Static

c). Heat exchanger

2). Avoidance of rapid saturated blowdown

3). Hardware development

d. Evaluate results of a, b and c

1). Tradeoffs

a). Feasibility and reliability

b). Payload effects

c). Costs and schedules

2). System recommendation

2.5.2 Orientation of LH_2 Using Screens

2.5.2.1 Introduction

It is proposed that DAC study the feasibility of using large screens for propellant orientation in order to reduce LH_2 orbital boiloff. Employment of screens may be useful in reducing the number of vents in a cyclic backup system (see 2. .1.4) and could conceivably lead to the elimination of fuel venting - thus providing a simple backup for continuous venting.

2.5.2.2 System Description

The basic feature of the system is a continuous screen jacketing the forward dome and the cylindrical portion of the fuel tank at a distance of about one or two inches. The fuel tank vent inlet extends into the main portion of the tank. A sketch of the system is presented in Figure 22.

Under low gravity conditions the propellant will wet the entire screen forming a barrier to vapor passage such that, when hydrogen is vaporized at the wall, pressures in the jacket and in the main part of the tank will be equalized by flow of liquid into the main part. This will result in creation of a vapor layer around the bulk of the liquid which will reduce heat input--possibly to the point at which no venting is required when combined with paint and insulation changes.

2.5.2.3 Study Effort

2.5.2.3.1 Conceptual Problems

A number of conceptual problems have arisen in preliminary investigations. Among these are uncertainty in regard to the ability of the screen to stay wetted and the possibility that the system could lead to stratification effects which would tend to increase boiloff. Problems of this type will be analyzed, possibly with the use of scale model testing.

2.5.2.3.2 Performance

Thermal performance of the system will be analyzed in detail and payload effects will be estimated.

2.5.2.3.3 Hardware

Problems regarding screen installation and associated schedule effects will be investigated.

2.5.3 Roll to Vent Cyclic

A third alternative to continuous venting involves the use of cyclic venting, but differs from the other approach in that the necessary propellant settling acceleration is provided by spinning the vehicle about its longitudinal (roll) axis. Preliminary studies have shown that in order to impart the required angular velocity to the LH_2, in a reasonable time, some type of longitudinal paddles (vanes) will be required in the LH_2 forward dome or perhaps along the entire length of the LH_2 tank. Any vane arrangement will be accompanied by an increase in the roll moment of inertia dependent upon the amount of LH_2 affected. Some of the more important design considerations consist of the roll rate requirements, vane arrangement, auxiliary propulsion system (APS) propellant requirement, and the required settling time. These parameters were investigated very briefly with the exception of the vane arrangement; which, although not studied was assumed to impart the required angular momentum to the liquid.

PROPOSED SCREEN CONFIGURATION

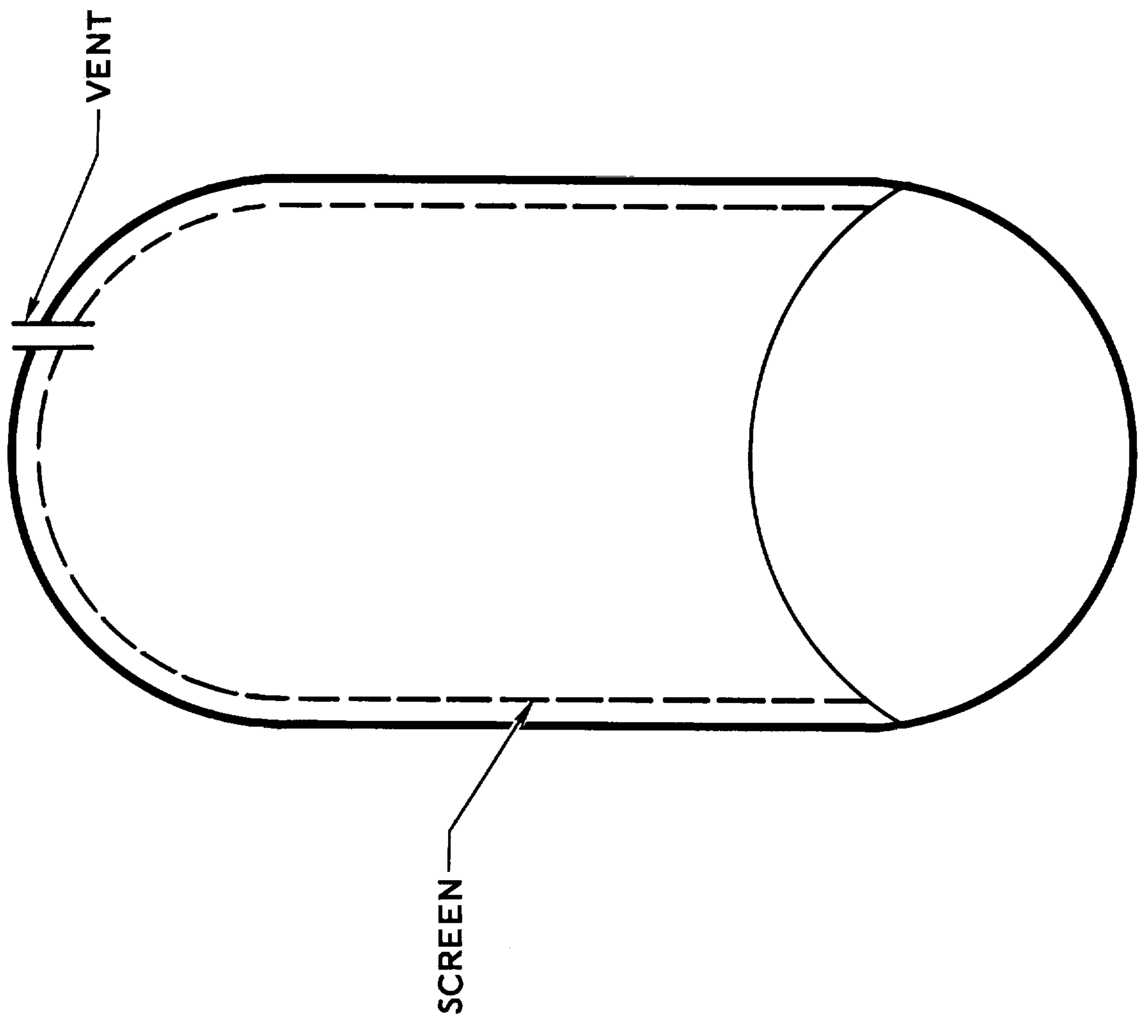


FIGURE 22

2.5.3.1 Roll Rate Requirements

The angular velocity (roll rate) requirement was based on the somewhat arbitrary consideration of establishing a bond number of 100 at a 6-foot radius from the LH_2 tank center line. (The 6-foot radius represents the approximate radius of an equivalent cylindrical ullage volume which would contain the LH_2 total ullage volume in the earth orbital condition). The roll rate requirement to obtain this Bond number was calculated as approximately 1.2 deg/sec. If this type of back-up system is chosen for further study additional analysis would be required to determine the dynamics of the fluid under low Bond numbers, and the time necessary to achieve fluid orientation with the low viscosity of liquid hydrogen.

In order to estimate the APS propellant requirements, the increase in the vehicle roll inertia was approximated by assuming the LH_2 to be completely settled against the tank wall in the form of an anulus. This results in approximately a 60 percent increase in the roll inertia. Based on this increased inertia and the previously stated roll rate, the APS propellant requirement was calculated as approximately 2.7 pounds/vent (I_{sp} = 285 sec).

2.5.3.2 Additional Considerations

Unfortunately, there is more involved then just the increased APS propellant requirement. Some of these additional considerations are listed below.

a. There is a weight penalty associated with the required LH_2 tank vanes

b. The increased roll inertia will increase the maneuvering propellant requirement by approximately 60 percent

c. No consideration has been given to the LOX tank vent requirements. If vanes also are required in the LOX tank, the roll inertia would be greatly increased with the accompanying increase in vent and maneuver APS propellant requirements.

d. There is the added complexity of pitch, yaw attitude control during venting. A minimum of control would at least seem to require the cancellation of any induced pitch and yaw disturbances.

e. A liquid/vapor separator probably will be required because the resulting fluid agitation will tend to keep the liquid/gas in or near a saturated condition.

f. The roll maneuvers required may tend to interfere with planned astronaut commanded maneuvers.

3.0 PROGRAM PLAN, NEAR ZERO G PROPELLANT CONTROL PLAN

Reference: Change Order 502

3.1 Description of Plan:

This Program Plan has been prepared to serve as a document for defining terms and conditions and for providing the information, documentation and planning necessary for conducting a test program on S-IVB-203 of near zero g propellant control equipment in conjunction with the LH_2 orbital experiment defined by Systems Development Plan 102. This equipment is to be incorporated into the DSV-4B-500 series as production hardware.

3.2 Purpose of Development Program:

The purpose of this experiment modification and the production design modifications is to develop a means for better control of cryogenic propellants during near zero g space flight conditions.

3.3 Development Program Requirements:

A. Design Requirements

The equipment should be designed using 2×10^{-5} g as the basic acceleration. The experiment will consist of six separate design efforts and equipment installations.

1. A flip-top screen and fixed deflector will be designed to baffle the main hydrogen feedline. This device will perform functions of filtering, antivortexing, and backflow diffusion. The flip-top is necessary to release the bubbles during the restart childown.
2. A peripheral "T" fitting will be designed to baffle the recirculation discharge line.
3. A baffle will be designed to be placed around the periphery of the hydrogen tank near the hydrogen level after the first burn. This baffle will be to a width limited by considerations of bubble formation during low g coast. Damping which it provides will be considered in computations of wave height after shutdown.

The damping effects of the baffle will be included in the slosh computations.

4. A deflector will be designed to be employed in the top of the hydrogen tank. The primary shape considered for this deflector will be a truncated cone with the hydrogen tank vent forward of the deflector. This installation will act as a low g slosh baffle if the hydrogen surface migrates toward the top of the tank.

   The maximum wave velocities will be determined.

5. A flip-top screen and deflector will be designed to be installed in the LOX sump vortex screen to allow venting of bubbles trapped under the vortex screen.

6. A stand pipe which acts as a simple type of hydrogen liquid/vapor separator and vent valve assembly will be designed. The stand pipe will extend from a location in the ullage to a port in the forward dome.

7. The time that the APS burning will be extended will be determined and the control system gains changed to minimize shutoff slosh.

8. The controls will be provided as required for the hydrogen liquid/vapor separator.

B. Test Program

1. Environmental and operational testing of the vent pipe/vent valve installation described in 3.3-A-6 above will be required.

2. The flip-top LH_2 device defined in Item 3.3-A-1 above will be environmentally tested.

3. The flip-top LOX device defined in Item 3.3-A-5 above will be environmentally tested.

4. The baffle described in 3.3-A-3 and the deflector described in 3.3-A-4 above will be evaluated by Engineering to establish the test program required to determine damping effectiveness, particularly for large amplitude sloshing such as is expected at boost termination and during coast.

C. Implementation

DAC in-house activities to implement this effort should conform to the following:

1. Design effort should continue following the criteria established in 3.3-A above.

2. A priority should be established via WRO to assure that the required equipment is manufactured early enough to assure a timely installation. Installation of the herein described equipment at Location A3 following checkout is highly recommended to preclude operational problems at Location A45 with out-of-sequence work.

3. The fabrication of this equipment shall be monitored and production delays reported to the cognizant program engineer.

4. The delivery commitment of the purchased hardware should be reviewed to assure that the fabrication and installation schedules will be met.

3.4 Schedule:

A. Production Effectivity

Items described in 3.3-A above are planned for S-IVB-203. This work package shall be incorporated in DSV-4B-501 and subsequent DSV-4B-500 series vehicles. The predicted schedule is shown in section 4.0.

B. General Installation Information

DAC shall perform a detailed evaluation of the steps required to perform these vehicle modifications on a retrofit basis for those vehicles that are out-of-phase in production.

Access will be required to the internal areas of both the LOX and the hydrogen tanks. It should be noted that in those cases where hydrogen tank insulation is installed in the vehicles at the time of the zero g propellant control equipment installation that segments of the insulation must be removed to allow the installation of the baffle. (Care should be taken to assure that this installation does not interfere with the operation of the equipment previously installed in the tanks, propellant utilization probes, point level sensors, etc.). This could best be confirmed by post installation checkout of the affected equipment.

4.0 SCHEDULE

The schedule for installation of the proposed hardware changes are as shown in Figure 23.* The reasons for the schedule change are as follows.

203 20 Additional calendar days (at 7 days/week) are required to install this change as this is additional out-of-position work. The twenty days will be spent on installations and recleaning of the tanks. This work will be added to the present post-firing mod period work package.

204 DSV-4B-203 goes late into the VCL at STC as a result of the above noted change.

501 15 Additional calendar days (at 7 days/week) will be required to install this change. Five days are gained due to an advance on the learning curve.

502 The installation is accomplished prior to stage checkout and results in delivery (1) one week late to STC.

206 No manufacturing impact is felt by -206 at SSC.

503 (1) One week impact is felt by -503 at SSC as this is the same installation as noted above on -502.

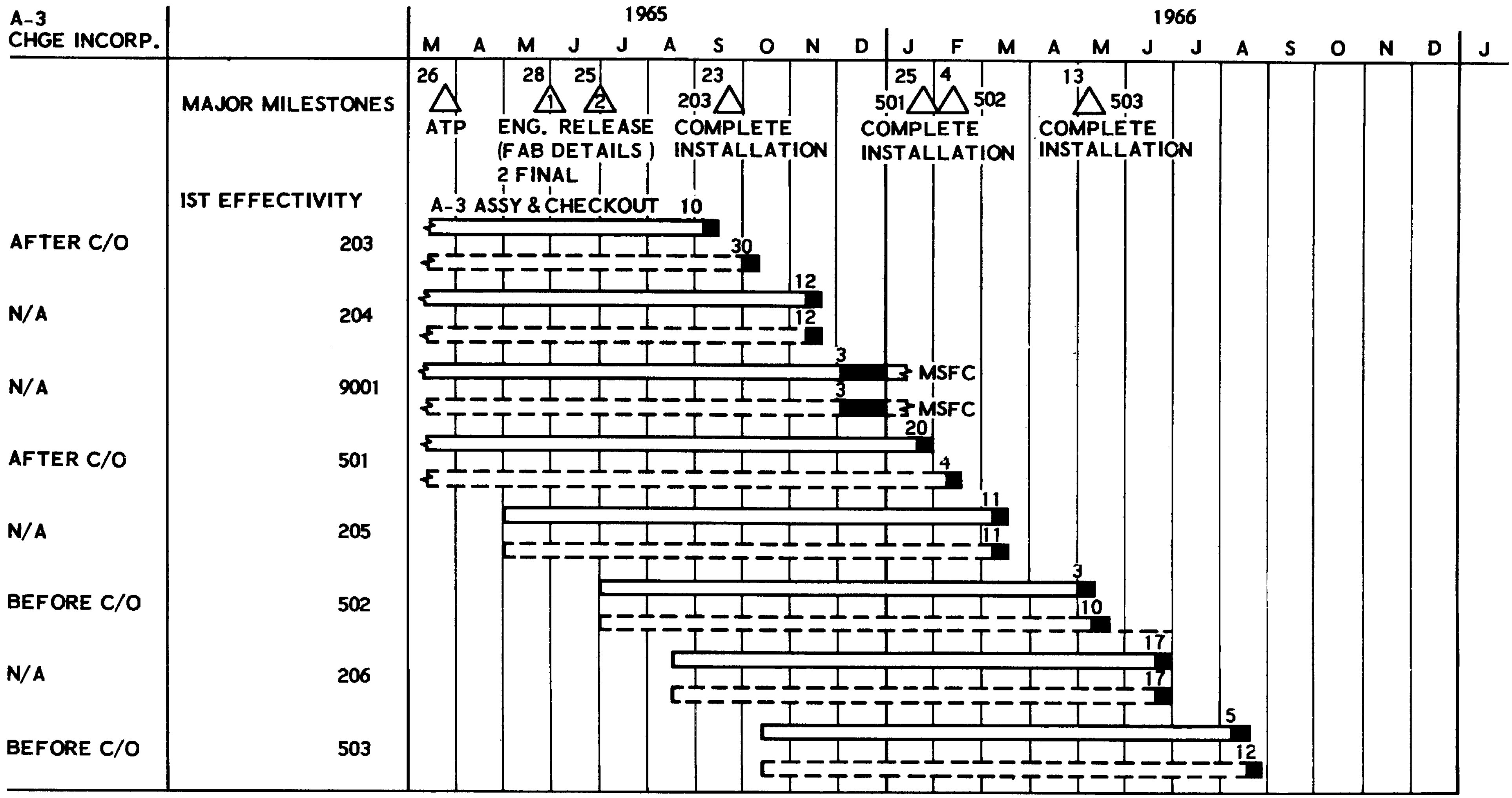
Premium time will be required for this entire effort.

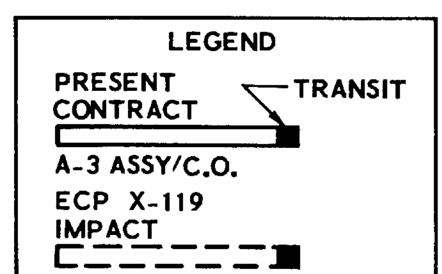
Appendix A - Mixing to Reduce Boiloff

The attached report was completed on 11-13-62 to determine the feasibility of inducing mixing in the LH_2 tank to reduce the number of vents required. The study was done, of course, for a cyclic venting concept. Although some of the quantitative values presented pertaining to the S-IVB stage are somewhat obsolete, (namely due to the fact that the cycles venting mode is no longer employed for the S-IVB) the results are still applicable to such a system. The cyclic venting concept is presently being investigated for use as a back-up system for the S-IVB.

*** Douglas is evaluating the work to be accomplished at STC to see if this effort can be accomplished in parallel with other tasks on a non-schedule interference basis. The schedule shown herein depicts the impact on affected vehicles if this installation is accomplished at the Space Systems Center.**

ESTIMATED DELIVERY SCHEDULE &IMPACT





ESTIMATED DELIVERY SCHEDULE
SLIPPAGE (DAYS) HUNTINGTON BEACH

203	20
204	0
9001	-
501	15
205	0
502	7
206	0
503	7

FIGURE 23

Introduction

A heat supply at the boundaries of a stagnant liquid hydrogen system creates a steep temperature gradient at the boundary due to the low thermal conductivity of liquid hydrogen. This temperature gradient causes the pressure of the system to increase quite rapidly with respect to time and, thus, shortens the time interval between vents.

The temperature gradient is reduced by creating a fully developed turbulence in the system so that the system is approximately in thermal equilibrium between vents. The pressure increase of the system with respect to time is now decreased and the time interval between vents is increased.

The Problem

The S-IVB tank in Figure 24 has to be vented 14 times over a period of 4.5 hours if the liquid hydrogen is stagnant, but only 4 times if the liquid hydrogen is mixed with its vapor and in thermal equilibrium. The maximum temperature increase of the liquid hydrogen between vents is 2°F. Thus, the problem is to keep the liquid hydrogen system in Figure 24 as close to thermal equilibrium as possible when heat flows across the boundaries. This should be accomplished by simple means and with a small weight penalty.

A Solution to the Problem

Consider the system in Figure 24. Fully developed turbulence exists in the liquid hydrogen system and heat flows across the boundaries 1, 2 and 3.

τ_t = turbulent sheat stress in lb_f/ft^2

g_c = gravitational conversion factor in $lb/_m ft/sec^2 lb_f$

V_b; V_a = velocity of fluid at the planes (a-a), (b-b) in ft/sec

LIQUID HYDROGEN SYSTEM - S-IVB TANK

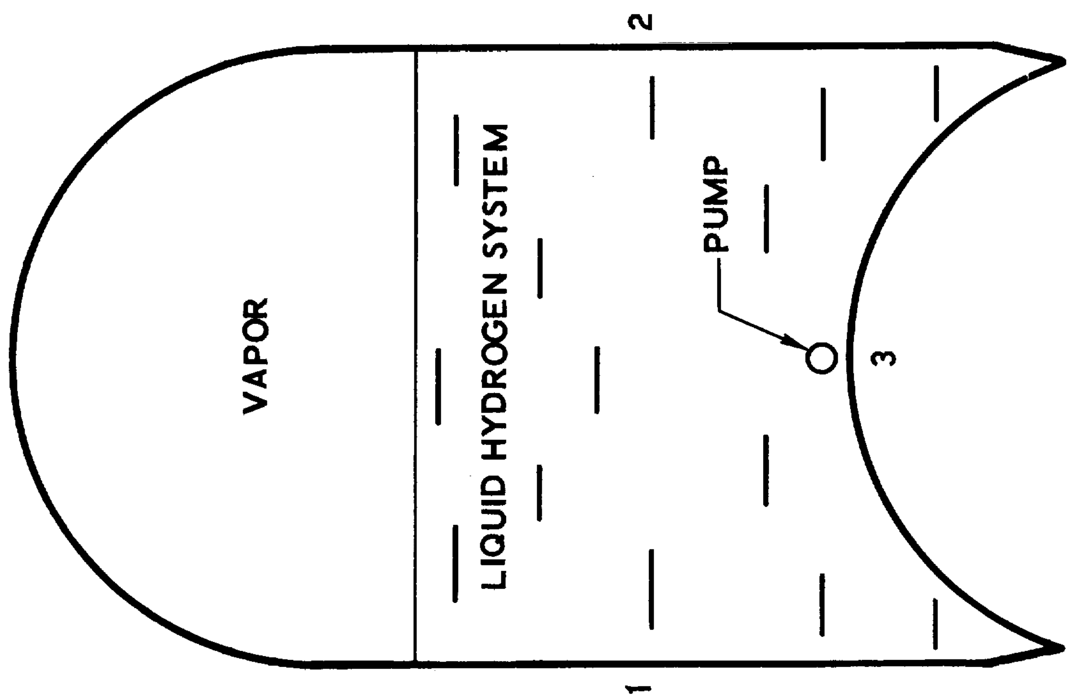


FIGURE 24

Eliminating the mass (m) between Eqs. (1) and (2) results in

$$Q_t = \tau_t \; C_p \; g_c \frac{(t_a - t_b)}{(V_a - V_b)} \tag{3}$$

$$Q_t = -\tau_t \; C_p \; g_c \frac{dt}{dv} \tag{4}$$

The shear stress in the laminar sublayer at the wall is

$$\tau = \frac{\mu}{g_c} \frac{dv}{dy} \tag{5}$$

where

τ = shear stress in lb_f/ft^2

μ = dynamic viscosity of fluid in lb_m/ft sec

$\frac{dV}{dv}$ = velocity gradient in laminar sublayer

The heat flow per unit area per unit time across a plane in the laminar sub-layer is

$$Q = -\frac{kdt}{dy} \tag{6}$$

where

Q = heat flow in $B/sec\ ft^2$

k = thermal conductivity of laminar sublayer in B/sec °F ft

$\frac{dt}{dy}$ = temperature gradient in laminar sublayer

Dividing Eq. (6) by Eq. (5) gives

$$Q = -\frac{\tau Kyc}{\mu} \; \frac{dt}{dv} \tag{7}$$

The turbulent exchange over a wall surface element may be pictured as in Figure 25. A certain mass (m) of the fluid passes per unit area and unit time through the plane (a - a) and flows to the plane (b - b). In the steady stage, the same amount of mass flows from the plane (b - b) to the plane (a - a). The fluid flows along the wall surface element with a mean velocity (V_t); the temperatures at the planes (a - a) and)b - b) are t_a and t_b, respectively, and the corresponding velocities are (V_a) and (V_b). The enthalpy of the mass (m) leaving the plane (a - a) is m $C_p t_b$. Thus, if t_a is greater than t_b, a net amount of energy (Q) is transported from the plane (a - a) to the plane (b - b). Hence,

$$Q_t = mC_p(t_a - t_b) \tag{1}$$

where

Q_t = energy transported from plane (a - a) to plane (b - b) in B/sec ft^2

m = mass of fluid passing through the plane (a - a) per unit time and unit area in lb_m/sec ft^2

C_p = specific heat of the fluid at constant pressure in B/lb °F. C_p at the plane (a - a) equals C_p at the plane (b - b)

t_a; t_b = temperature at the planes (a - a); (b -b) in °F

Because of the turbulence, a shear stress is acting on the plane (c - c). The mass (m) leaving the plane (a - a) acquires the velocity (V_b) and the mass (m) leaving the plane (b - b) acquires the velocity ($_a$). If the velocity V_b is greater than the velocity V_a, the turbulent shear stress is

$$\tau_t = \frac{m}{gc} (V_b - V_a) \tag{2}$$

Thus, $Q_t/\tau_t = Q/\tau$ if $K/\mu = C_p$ or if the Prandtl number $C_p\mu/K = 1$. If the thickness of the laminar sublayer at the wall is small, $Q_t/\tau_t = Q/\tau = Qw/\tau_w$ and Eq. (4) can be applied to find the relationship between the temperature in the turbulent region, and the temperature at the wall for a fluid with a Prandtl number of one or close to one. Integrating the temperature (t) from

TURBULENT FLOW OVER A SURFACE ELEMENT

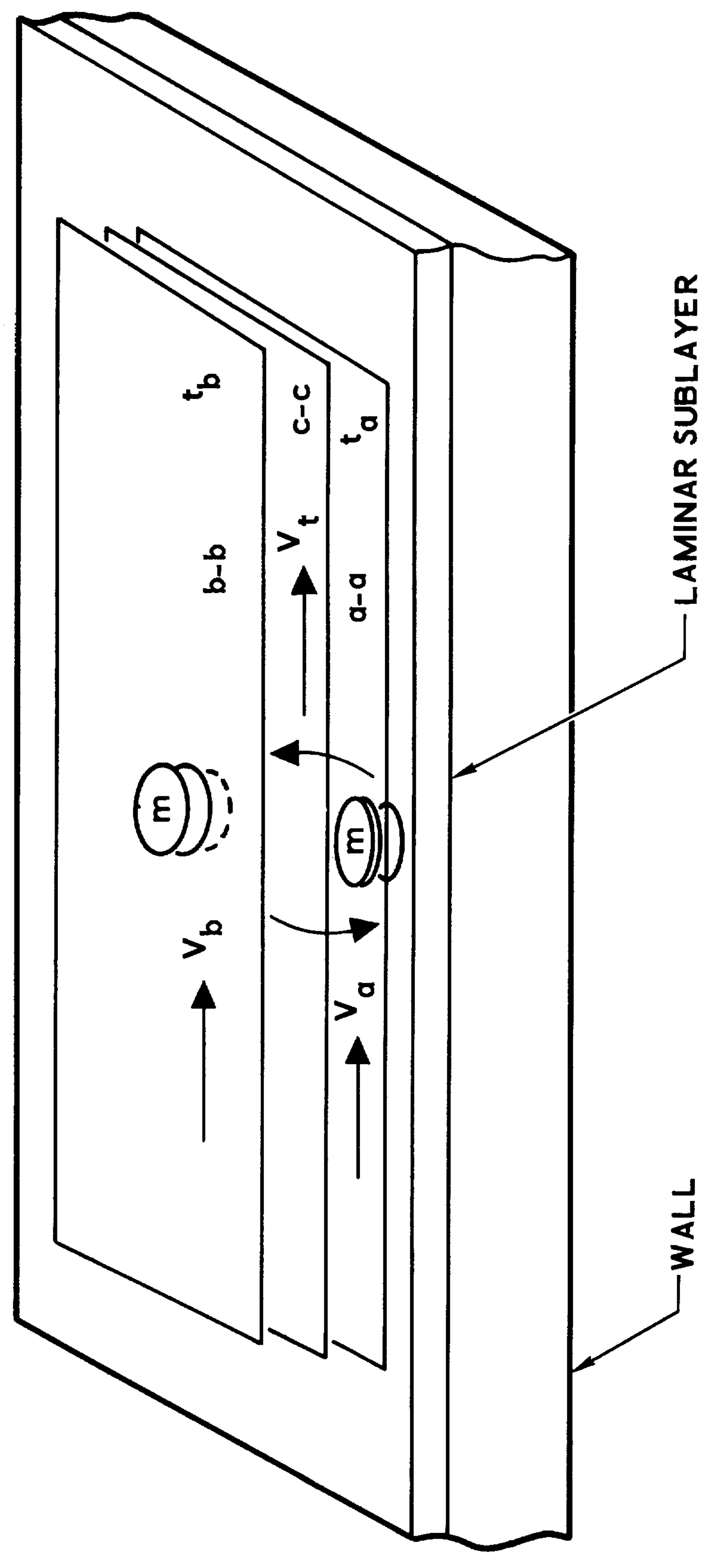


FIGURE 25

(t_w) to (t_t) and the velocity (V) from zero to (V_t) in Eq. (4) results in

$$t_w - t_t = \frac{Q_w V_t}{\tau_w C_p} \tag{8}$$

where

t_w = wall temperature in °F

t_t = temperature in turbulent region of the fluid flowing over the wall surface element in °F

V_t = average velocity of fluid flowing over the wall surface element in ft/sec

The relationship between the thickness (y) of the laminar sublayer and the velocity (V_t) is expressed by, (ref. 1)

$$y = \frac{5\mu}{v \rho gc} \tag{9}$$

$$y = \frac{5\mu}{\tau_w^{\frac{1}{2}} \rho^{\frac{1}{2}} gc} = \frac{25\mu}{V_t \rho gc} \tag{10}$$

where

y = thickness of laminar sublayer in ft

τ_w = $\mu V_t/gcy$ in lb_f/ft^2

ρ = density of fluid in $slugs/ft^3$

The fully developed turbulence in the liquid hydrogen system is created by 24 three dimensional free jets which emerge from three pumps placed in the vicinity of the tank bottom as shown in Figure 24. The flow is turbulent within the jet boundaries and the constant velocity profile at the jet efflux is steadily decreasing due to the gradual entrainment of fluid from the surroundings.

The maximum velocity (V_{max}) of the jet at a distance (X) from the jet efflux is calculated from (ref. 2)

$$V_{max} = \frac{6.2\ V_o\ D_o}{X} \tag{11}$$

where

V_{max} = Velocity of jet at the center line of the jet in ft/sec

V_o = Efflux velocity of jet in ft/sec

D_o = Diameter of jet at efflux in ft

X = Distance from jet efflux in ft

The velocity V_x at a distance (X) from the jet efflux and at a radius (r) from the centerline of the jet is calculated from

$$\mathrm{Log}\ \frac{V_x}{V_o}\ \frac{X}{D_o} = 0.79 - \frac{33\ r^2}{X^2} \tag{12}$$

where

V_x = Velocity of jet at a distance (X) from the jet efflux and at a radius (r) from the centerline of the jet in ft/sec

The pressure difference (Δ P) across the pump is calculated from

$$\Delta P = \frac{V_o^{2} \rho}{2} \tag{13}$$

where

P = Pressure difference across the pump in lb_f/ft^2

The power output (P_p) of the pump is

$$P_p = 1.36 \times 10^{-3} \quad v \, \Delta P \tag{14}$$

where

P_p = Power output of pump in KW

$\dot{\omega}$ = Flow rate in slugs/sec

V = Specific volume of fluid in ft^3/slug

CALCULATIONS

The liquid hydrogen system in Figure 24 has a Prandtl number of 1.16 and, hence, Equation (8) is used to calculate the temperature difference $(t_w - t_t)$. The diameter of the jet at the efflux is 1 inch and the maximum velocity of the jet at a distance 18 feet from the jet efflux is 1 ft/sec. This distance is the maximum distance from the jet efflux to the system boundaries.

The efflux velocity (V_o) of the jet is calculated from Equation (11). Thus,

$$V_o = \frac{18.12}{6.2} = 35 \text{ ft/sec}$$

The flow is turbulent since the Reynolds number = 9.85×10^5. The pressure increase across the pump and the power output of the pump, calculated from Equations (13) and (14) are 0.58 psi and 0.173 KW, respectively.

The total power output of the three pumps is 0.519 KW. The velocity distribution and width of a jet, at a distance of 18 feet from the jet efflux, is calculated from Equation (12) and is shown in Figure 26. The mean velocity (V_t) of the jet at this distance is 0.46 ft/sec.

VELOCITY PROFILE OF TURBULENT JET
18 FT FROM JET EFFLUX

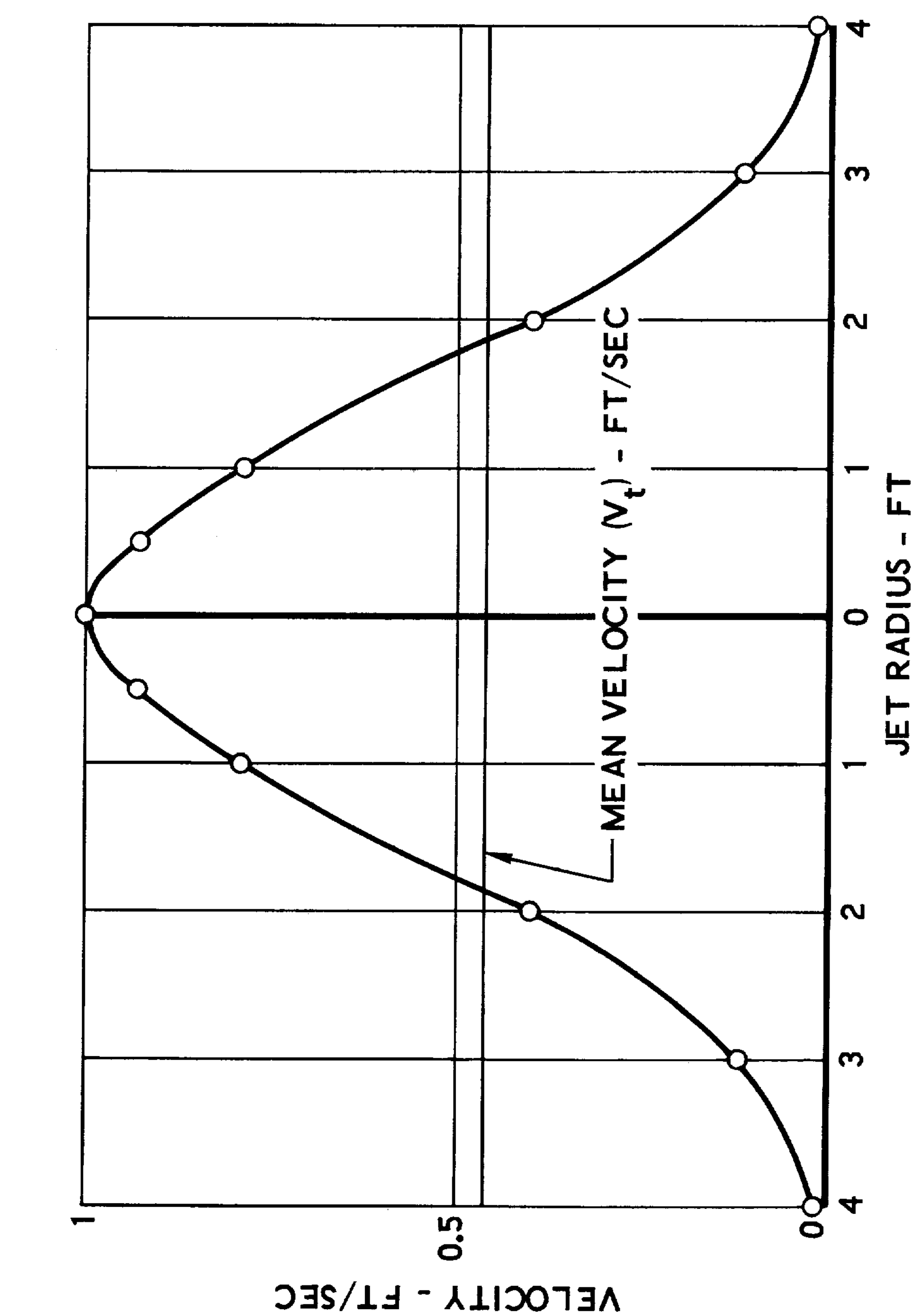


FIGURE 26

Using the above value of $(V_t)_1$ the thickness (y) of the laminar boundary layer is calculated from Eq. (10). Thus,

$$y = \frac{25 \times 875 \times 10^{-8} \times 12}{4.4 \times 0.46} = .0013''$$

The energy stored by the system with respect to time is shown in Figure 27. The effect of supplied pumping power to the system is also shown in this figure. It is seen from Figure 5 that the heat supply (Q_W) to the system is greatest during that time interval which proceeds the first vent. The mean value of (Q_W) during this time interval is used to calculate the temperature difference $(t_w - t_t)$ from Eq. (8). Thus,

$$(t_w - t_t) = \frac{0.024 \times 0.46}{0.00115 \times 2.4 \times 32.2} = 0.125^{\circ}F$$

The volume flow rate for each pump is 685 gal/min and the pressure increase across the pump is about 0.6 psi. A suitable pump for this type of operation has an efficiency of about 30-35% and a weight, including electric motor, of about 30 lbs. The required power supply to the pump is 1.8 KW when the pump efficiency is 30%. The main characteristics of the flow in the liquid hydrogen system is shown schematically in Figure 28.

If the liquid hydrogen in Figure 1 is completely mixed with the vapor, the temperature difference $(t_w - t_t) = 0.065^{\circ}F$. The maximum velocity of the jet at the maximum distance from the jet efflux is 1 ft/sec. and the mean velocity of the jet is 0.49 ft/sec. The required power supply under these conditions is 3.75 KW for a pump efficiency of 30%.

The total weight of pumps and power supply, when the liquid hydrogen is separated from the vapor, is about 200 lbs. The corresponding weight for the mixture of liquid hydrogen and vapor is about 300 pounds. These calculations are based on a power supply of zinc-silver oxide batteries for driving the pumps. The actual energy density of these batteries is 0.08 KW hr/lb.

ENERGY STORED IN MIXED LIQUID HYDROGEN SYSTEM VS TIME

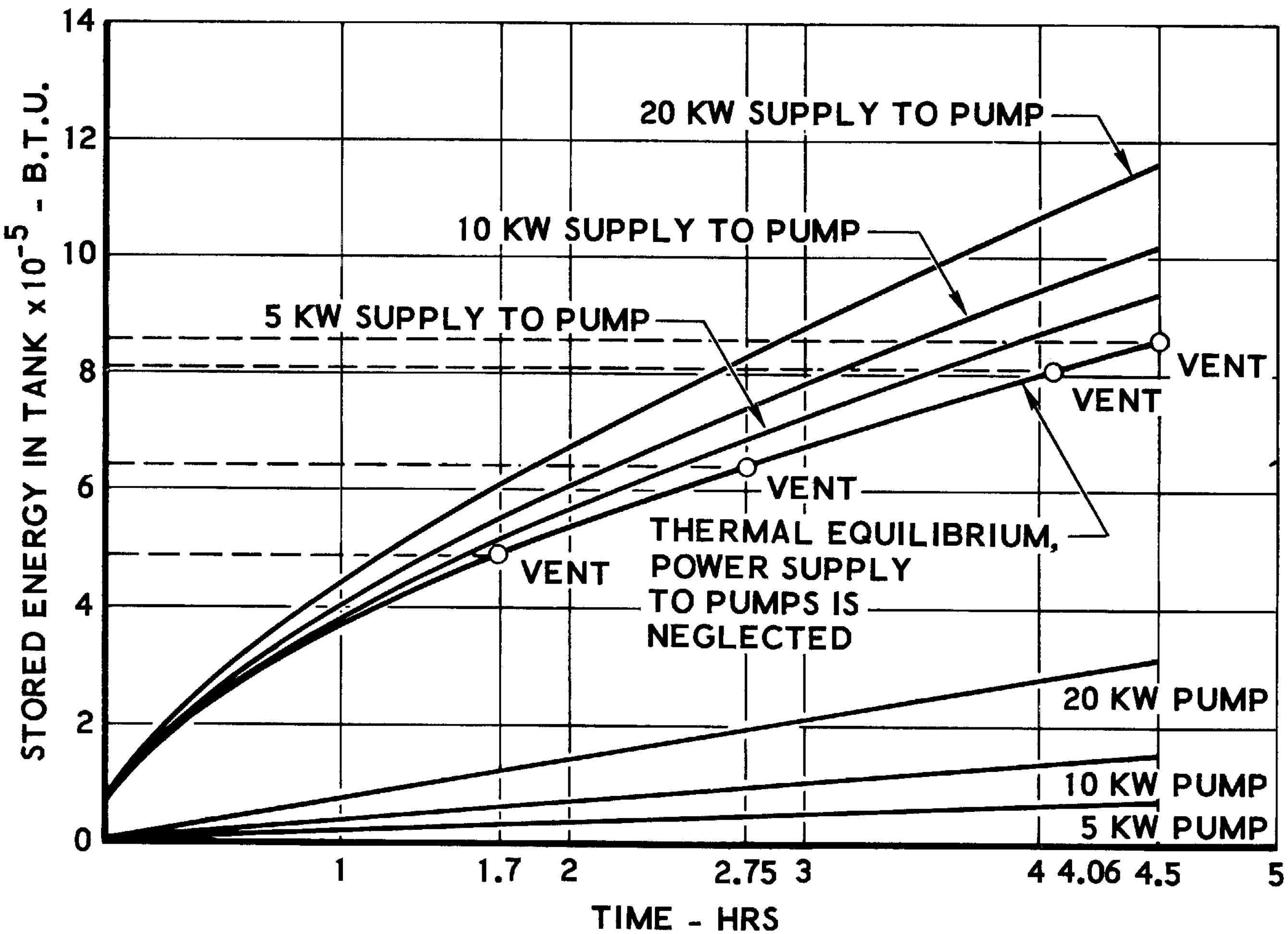


FIGURE 27

TURBULENCE IN LIQUID HYDROGEN SYSTEM

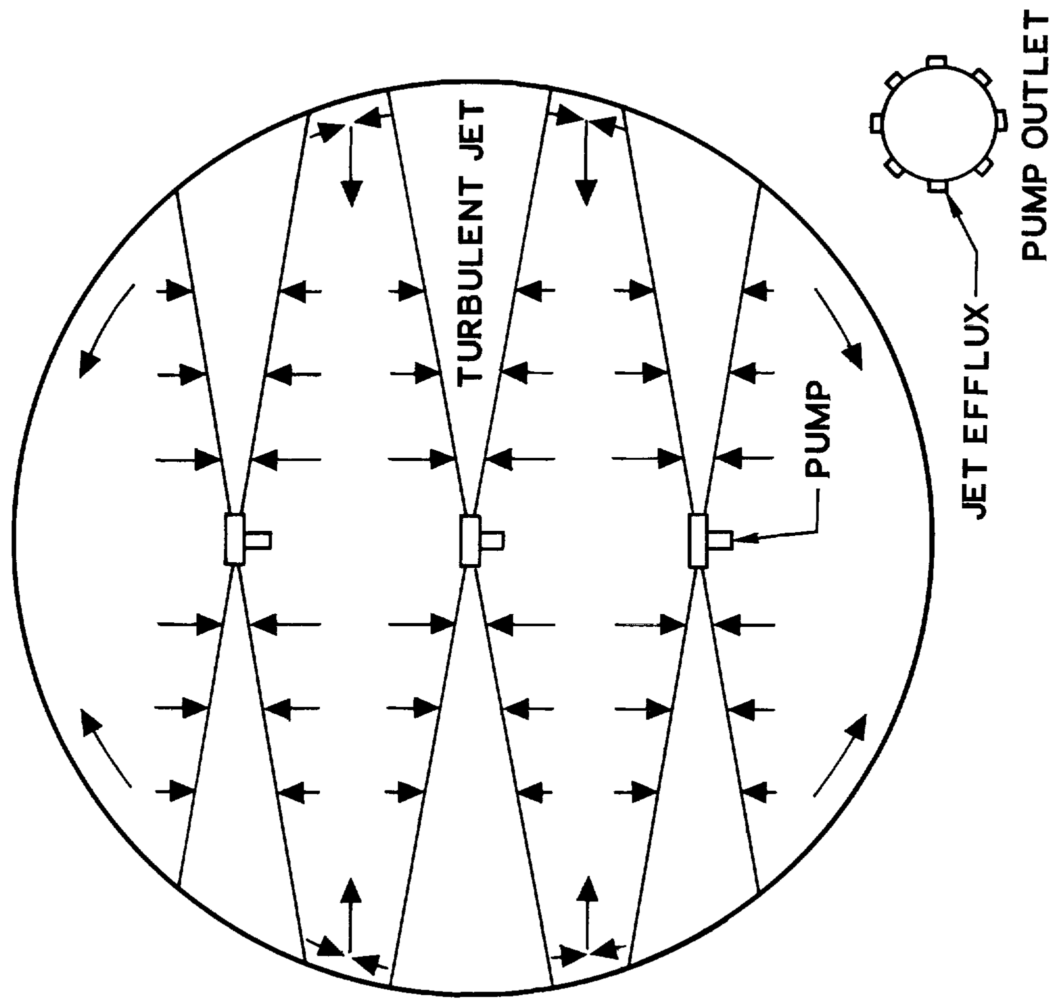


FIGURE 28

The hydrogen lost due to venting is about 2,400 pounds when the liquid hydrogen system in Figure 24 is stagnant and about 2,100 pounds when the system is in the turbulent state.

The hydrogen lost due to venting, when the vapor is in the center of the tank and the total inside surface of the tank is wetted, is about 4,000 pounds with no turbulence. The hydrogen lost due to venting when the vapor and liquid hydrogen is mixed and in a turbulent state is about 3,500 pounds. However, the number of vents in the stagnant case are 15 while the number of vents are only 4 if the system is in the turbulent state.

The power input to the pumps is dissipated as heat to the system and increases the rate of pressure increase of the system with respect to time. This effect can be eliminated by increasing the thickness of the insulation material for the S-IVB tank. The resulting weight increase of the insulation material is about 20 pounds for the unmixed system and about 30 pounds for the mixed system. The weight of pumps and batteries for the unmixed and mixed systems are about 200 pounds and 300 pounds, respectively. There is a weight penalty of 50 pounds per vent for the mixed system, since the vapor and liquid have to be separated just before the vent occurs. Thus, the weight saving for the unmixed turbulent system is about 80 pounds and the weight saving for the mixed turbulent system is about 720 pounds.

RESULTS

This study leads to the following results:

1. Turbulence is created by simple means in both the unmixed and mixed systems of the S-IVB tank with an acceptable weight penalty.

2. The temperature difference between the inside surface of the S-IVB tank and the turbulent flowing fluid over the surface is about 0.1°F or less for a boundary layer thickness of about 0.001 inch.

3. The weight of the pumps, plus power supply is about 200 pounds when turbulence exists in the liquid hydrogen only (liquid hydrogen and vapor are separated by a small gravitational force). The corresponding

weight is about 300 pounds when the liquid hydrogen is mixed with the vapor and turbulence exists in the mixture. The power supplies for the two cases are about 1.8 KW and 3.8 KW, respectively, and are based on a pump efficiency of 30%.

4. The creating of turbulence in the unmixed and mixed systems of the S-IVB tank results in a weight saving of the systems of about 80 pounds and 720 pounds, respectively.

DISCUSSION OF RESULTS

The above calculations show that the temperature difference (t_w - t_t) between the wall and the turbulent flowing fluid over the wall surface is a function of the laminar boundary layer thickness. Thus, the inside surface of the S-IVB should have a profile such that no deep valleys exists where the fluid can be trapped and heated.

It is seen from Eq. (1) that the mass exchange (m) between any two adjacent planes of the core of the unmixed or mixed systems of Figure 1 should be high in order to keep the temperature difference between the two planes very small. The small temperature increase of $2^{\circ}F$ of the systems before and between vents imposes this requirement. It is expected that the flow of fluid in to the turbulent jets and the suction action of the pumps will provide sufficient mass exchange to satisfy this condition.

The calculated temperature difference (t_w - t_t) between the inside tank surface and the turbulent flowing fluid over the surface is conservative because the calculation is based on the maximum distance between the jet efflux and the tank wall. The mean velocity of the jet increases as this distance decreases. This results in a smaller thickness of the laminar sublayer and a smaller temperature difference (t_w - t_t) where the wall surface intercepts the jet.

The weight of the power supply can change since it is a function of the pump efficiency and battery performance. For instance, if the pump efficiency is 50% instead of 30% and the manufacturers ultimate goal of 0.095 KW hr/lb for the zinc-silver oxide battery is reached, the weight of the power supply will become about 50 pounds for the unmixed system and about 100 pounds for the mixed system of the S-IVB tank.

CONCLUSION

The following conclusions are drawn from this particular study of the S-IVB.

1. By means of turbulence, it seems possible to obtain a temperature difference of about $0.1^{\circ}F$ between any two points of the systems at any time during the time interval between the vents.

2. Neglecting the above small temperature difference and considering the systems to be in thermal equilibrium at any instant, the weight saving for the unmixed and mixed systems of the S-IVB is about 80 pounds and 720 pounds, respectively.

RECOMMENDATIONS

The following is recommended:

1. A test setup should be constructed in order to determine the temperature distribution under actual conditions. It may be that the turbulence will be more than enough in some regions and not sufficient in other regions if the jets are directed as shown in Figure 3. This condition can be corrected by changing the directions of the jets until an even turbulence exists in the systems.

BIBLIOGRAPHY

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2. Rouse, J., "Free Jets" Proc. Am. Soc. Civil Engrs. 74, 1571, 1948

APPENDIX B

VAPOR ENTRAINMENT IN THE BULK OF THE LIQUID DUE TO BOILING AT THE TANK WALLS AND ANTI-SLOSH BAFFLES

The Saturn V/S-IVB and Saturn IB/S-IVB-203 hydrogen tanks employing an orbital constant pressure continuous venting system were analyzed to determine the effect of heat input into the tank on propellant settling characteristics.

1. Description of the Continuous Venting System

The continuous venting system vents vapor continuously during the orbital coast period. The vapor supply is replenished by the heat input into the tank vaporizing liquid at the tank walls and by evaporation at the liquid-vapor interface. The thrust produced by venting the vapor continuously exerts a buoyant force on the vapor bubbles at the tank wall and imparts a certain velocity to these bubbles in the direction of the ullage space. The thrust also causes boundary layer flow in the liquid at the tank wall. A schematic diagram of the continuous venting system is shown in Figure 29.

After the orbital injection, the two phase boundary layer at the tank wall will grow in size until it reaches equilibrium. For the purpose of this analysis, it is assumed that a) there are no temperature gradients in the boundary layer, b) the liquid velocity in the boundary layer is zero, and c) there is no evaporation at the liquid-vapor interface. With these assumptions, liquid evaporation at the tank walls is the only vapor-producing mechanism. This is conservative for the liquid settling analysis.

It will be shown that the shape of the hydrodynamic boundary layer at the wall can be represented as a function of length along the wall. The boundary layer thickness will depend on the bubble velocities in the boundary layer, which in turn depend on the acceleration level. If the bubble velocities are low, large amounts of vapor will be located at the tank wall and the boundary layer will extend deep into

SCHEMATIC DIAGRAM OF THE CONTINUOUS VENTING SYSTEM

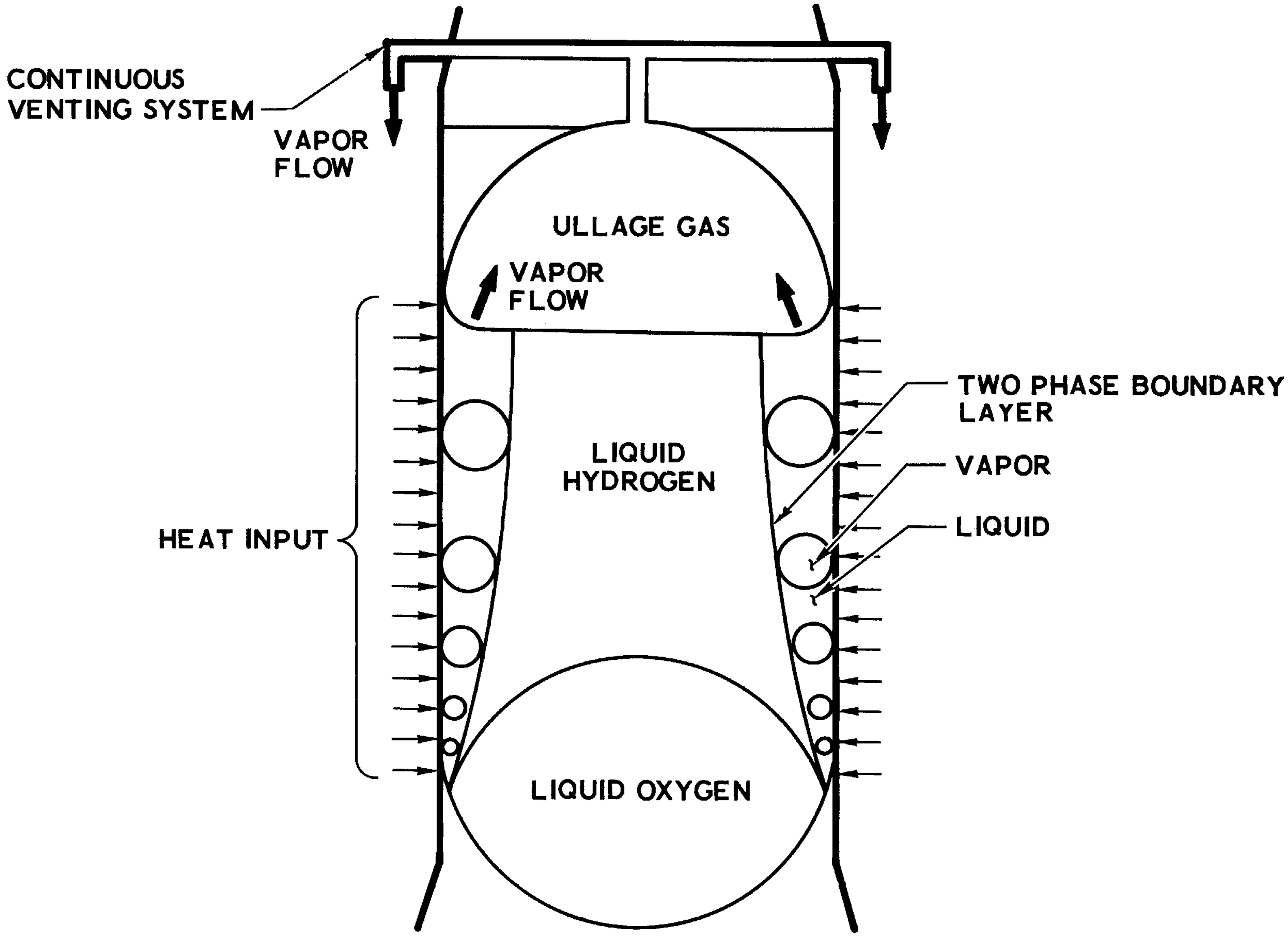


FIGURE 29

the bulk of the liquid. Such a condition would be undesirable since it may approach a condition where all of the vapor in the hydrogen tank would be located in the boundary layer and none in the ullage space. This would cause liquid hydrogen to be vented periodically. The continuous venting system was analyzed to determine the effect of the above mentioned parameters on the performance of the continuous venting system. A constant pressure, variable orifice area system was assumed. The present continuous venting system design calls for a constant pressure venting system.

2. Heat Input into the Hydrogen Tank

The orbital heat input rate into the hydrogen tank as a function of time is shown in Figure 30. This heat input is based on the maximum orbital heating rate. The high initial heat input rate is caused by the heat stored in the skin and insulation during the boost phase. The heat input rate can be approximated by the following expression:

$$Q = 70\ e^{-0.000495t} + 32$$

The above expression is plotted in Figure 30. It is evident that this expression represents the heat input with reasonable accuracy.

3. Bubble Velocity in a Reduced Gravity Field

The behavior of the continuous venting system depends to a large degree on the velocity of bubbles in the boundary layer. The following equation (Reference a) describes the bubble velocities:

$$u_x = \lambda\sqrt{gD_x}$$

The value of λ must be determined experimentally. In a normal gravity field, this value varies from 0.35 for large bubbles in small tubes to 0.72 for bubbles in infinite fluid medium. For the system being analyzed, a of 0.72 is applicable since the tank diameter is much larger than the maximum predicted bubble diameter.

ORBITAL HEAT INPUT RATE INTO THE SATURN V/S-IV B HYDROGEN TANK

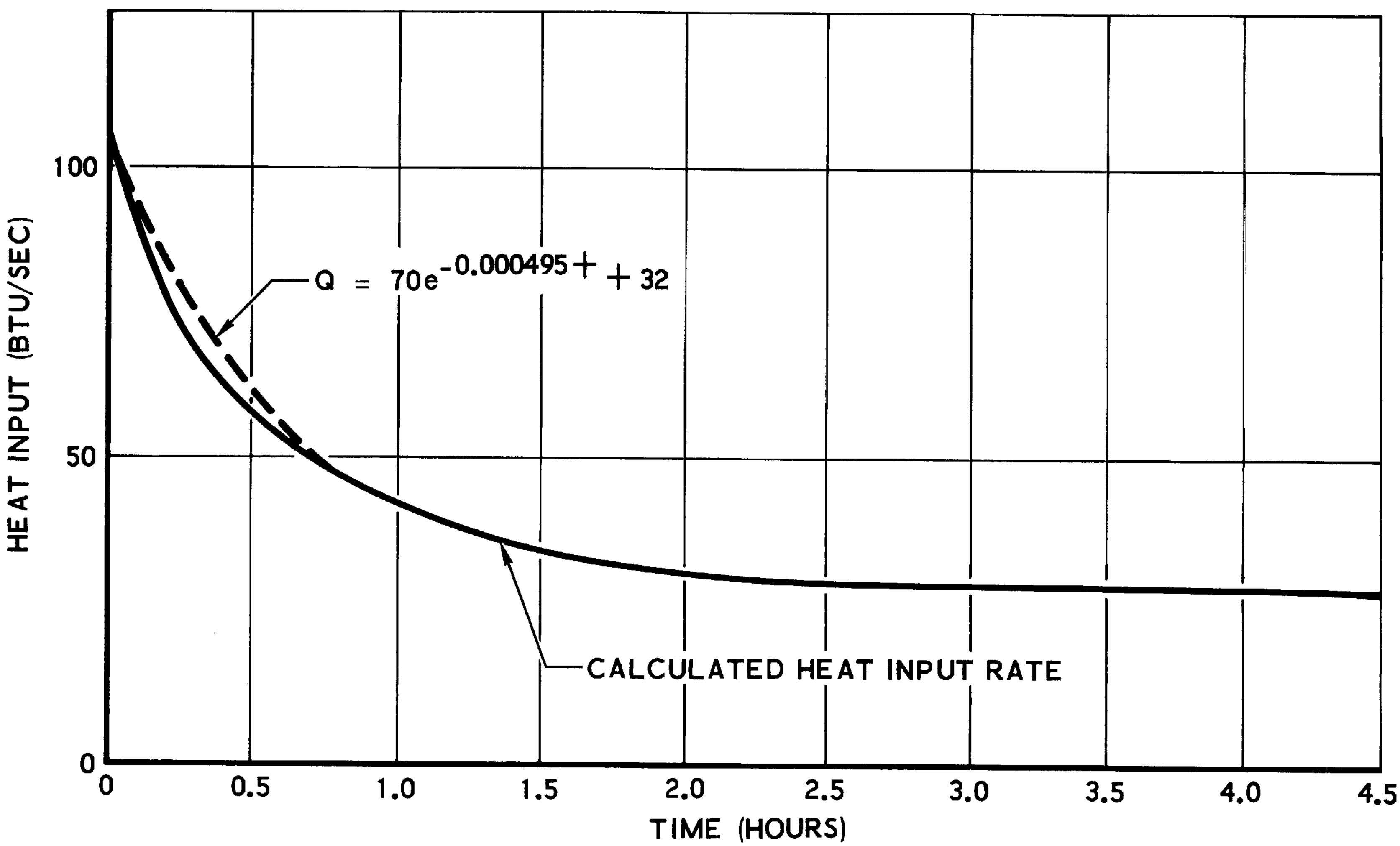


FIGURE 30

4. The Boundary Layer Quality

The boundary layer quality, which is the ratio of vapor to total mass, is difficult to predict. The boundary layer quality must either be assumed or treated as a parameter. Reference b makes the following statement about the boundary layer quality:

> "The boundary layer quality, the relative velocity between vapor and liquid, and, of course, the profile shapes remain as parameters in these analyses. Further investigation of the boiling phenomena, especially the boundary layer quality, will be required to produce an explicit boundary layer solution."

Closely related to the quality of the boundary layer are the bubble sizes in the boundary layer. These sizes must be established in order to predict the bubble velocities. Both the boundary layer quality and the size of the bubbles in the boundary layer must be known in order to predict the boundary layer characteristics.

Although it is not possible to calculate the quality and the bubble diameters directly, some estimates can be made from qualitative considerations. The heat input into the tank vaporizes liquid at certain rate. This vapor is probably created in the form of relatively small bubbles. Since the acceleration level is low and the bubbles are small, these bubbles will have low velocities in the direction of the acceleration gradient. The length of time that a bubble exists in the vicinity of another bubble provides a good opportunity for bubble coalescence or formation of bubble bundles. As bubbles coalesce, their velocities increase, since the bubble velocity is proportional to the square root of the bubble diameter. The larger bubbles, moving at larger velocities than small bubbles, will coalesce with smaller bubbles that they encounter. These arguments suggest that the bubbles in the boundary layer will probably be very large. The bubbles will be spaced a certain distance apart. Experimental evidence indicates that a bubble rising in a fluid in a gravity field behind another bubble will catch up and coalesce with the first bubble if the initial spacing of the bubbles is too small. Hence, closely spaced bubbles in the boundary layer will coalesce.

Based on the qualitative considerations presented thus far, the following assumptions were made about the quality and bubble sizes in the boundary layer:

a. All bubbles at any given point along the boundary layer are equal in diameter.

b. There is only one bubble at any given point extending from the tank wall to the edge of the two phase region. This is shown schematically in Figure 1.

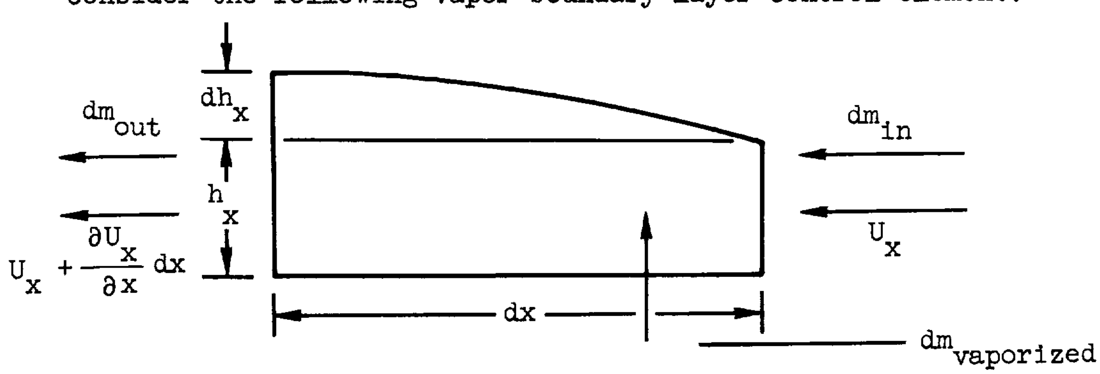
c. The bubbles are assumed to be spaced one bubble diameter apart.

5. The Boundary Layer Shape

The shape of the two phase hydrodynamic boundary layer can be determined by making a mass balance on the vapor in the boundary layer. For the purpose of this analysis, it is assumed that all vapor exists as a vapor film instead of discrete bubbles. This makes the approach convenient mathematically. At any given point in the boundary layer, the boundary layer thickness (which is also equal to the assumed bubble diameter at that point) will be proportional to the vapor film thickness. For the assumption that all bubbles are spaced one bubble diameter apart, the following relationship exists between the boundary layer thickness and the hypothetical vapor film:

$$h_x = A_1 D_x = \frac{\pi}{12} D_x$$

Consider the following vapor boundary layer control element:



Assume that the boundary layer shape is independent of time. The gravity level, hence, also the boundary layer thickness, will vary with time. However, the time transients in this particular application are rather mild and the boundary layer shape can be estimated by a series of steady state solutions that are independent of time.

$$dm_{in} = \rho u_x h_x dt$$

$$dm_{out} = (\rho u_x + \rho \frac{\partial u_x}{\partial x} dx)(h_x + dh_x) dt$$

$$dm_{vaporized} = \frac{q}{L} dxdt$$

$$dm_{in} + dm_{vaporized} - dm_{out} = 0$$

$$\rho u_x h_x dt + \frac{q}{L} dxdt - (\rho u_x + \rho \frac{\partial u_x}{\partial x} dx)(h_x + dh_x) dt = 0$$

Eliminating higher order differentials,

$$\frac{q}{L} - \rho u_x \frac{dh_x}{dx} - \rho \frac{\partial u_x}{\partial x} h_x = 0$$

$$u_x = \lambda\sqrt{gD_x} = \lambda\sqrt{\frac{12}{\pi} gh_x}$$

$$\frac{\partial u_x}{\partial x} = \frac{1}{2} \lambda(\frac{12}{\pi} gh_x)^{-1/2} \frac{12}{\pi} g \frac{dh_x}{dx}$$

$$\frac{q}{L} = \rho \frac{\lambda}{2}\sqrt{\frac{12}{\pi} gh_x} \frac{dh_x}{dx}$$

$$\int_0^x \frac{q}{L} dx = \rho \frac{\lambda}{2}\sqrt{\frac{12}{\pi} g} \int_0^{h_x} h_x^{\frac{1}{2}} dh_x$$

Integrating,

$$h_x = \left(\frac{3q}{\rho L \lambda (12 g/\pi)^{\frac{1}{2}}}\right)^{2/3} x^{2/3}$$

It is obvious that the boundary layer shape can be represented by an equation of the following form:

$$h_x = A_2 \, x^{2/3}$$

$$\int_0^{Vw} dV_w = c \int_0^S h_x dx = c \int_0^S A_2 \, x^{2/3} \, dx$$

$$V_w = 3/5 \, cA_2 \, S^{5/3}$$

$$A_2 = 5/3 \frac{Vw}{cS^{5/3}}$$

$$h_x = 5/3 \frac{Vw}{cS^{5/3}} \, x^{2/3}$$

6. <u>Derivation of the Continuous Venting System Equations</u>

The continuous venting system is analyzed by solving the following equations simultaneously:

a. Conservation of vapor mass in the tank

b. Conservation of vapor mass in the boundary layer

1. <u>Conservation of Vapor Mass in the Tank</u>

$$dm_1 = dm_3$$

$$dm_1 = \frac{Q}{L} dt$$

$$Q = 70_e^{-0.000495t} + 32$$

$$dm_1 = (70_e^{-0.000495t} + 32) \frac{dt}{L}$$

$$\frac{70_e^{-0.000495t} + 32}{190} = A_e P_e C_D \sqrt{\frac{\gamma g o}{RT_e}}$$

$$\frac{70_e^{-0.000495+} + 32}{190} = A_e \times 0.487 \times 0.9P \sqrt{\frac{1.67 \times 32.2}{766.8 \times 0.749t}}$$

$$A_e = (2.74\ e^{-0.0004956} + 1.25)\ \frac{T}{P}$$

2. <u>Conservation of Vapor Mass in the Boundary Layer</u>

$$dm_1 = \frac{Q}{L}\, dt$$

$$dm_2 = \rho\, u_s c h_s dt$$

$$u_s = \lambda \sqrt{\frac{12}{\pi}\quad gh_s}$$

$$h_x = 5/3 \qquad \frac{V_w}{cS^{\ 5/3}} \quad x^{\ 2/3}$$

$$h_s = 5/3 \quad \frac{V_w}{cS}$$

$$dm_w = \frac{8}{L}\, dt\ - \rho\lambda c \sqrt{\frac{12}{\pi}\ g}\ \left(5/3\ \frac{V_w}{cS}\right)^{3/2} \quad dt$$

$$m_w = \rho V_w$$

$$dm_w = \rho dV_w$$

$$\rho dV_w = \frac{Q}{L}\, dt\ -\ \rho\lambda c \sqrt{\frac{12}{\pi}\ g}\ (5/3\ \frac{V_w}{cS})^{3/2} \quad dt$$

$$g = 1.4 \times 10^{-4}\ A_e P \eta$$

$$g = 1.4 \times 10^{-4} \sqrt{T}\, (2.74\ e^{-0.000495t} + 1.25)\eta$$

$$\rho dV_w = (70\ e^{-0.000495t} + 32)\ \frac{dt}{L} - \rho\lambda c\sqrt{\frac{12}{\pi}}$$

$$\sqrt{1.4 \times 10^{-4}\ (2.74\ e^{-0.000495t} + 1.25)\eta}\ \sqrt[4]{T}\left(5/3\ \frac{V_w}{cS}\right)^{3/2}\ dt$$

1) $$\frac{dV_w}{dt} = (70\ e^{-0.000495t} + 32)\frac{1}{\rho L} - \lambda c\sqrt{5.34 \times 10^{-4}\ (2.74\ e^{-0.000495t} + 1.25)}\ \sqrt[4]{T}\left(5/3\ \frac{V_w}{cS}\right)^{3/2}$$

A Fortran program was written to solve Equation 1. It was assumed that the hydrogen in the tank is in a saturated state at the time of injection into orbit. An initial pressure of 21 psia was assumed.

The results of the analysis are presented in Figures 31 and 32. Figure 31 represents the vapor volume entrained in the bulk of the Saturn V/S-IVB liquid hydrogen. Figure 32 represents the vapor volume entrained in the bulk of the Saturn IB/S-IVB-203 liquid hydrogen. These figures represent only the vapor entrained in the bulk of the liquid due to boiling at the tank walls.

7. Vapor Volume Entrained Under the Anti-Slosh Baffle

In addition to the vapor entrained in the bulk of the liquid due to boiling, some vapor will be entrained under the anti-slosh baffle. Two methods were used to calculate the vapor volume under the anti-slosh baffle as a function of baffle depth. These methods are:

a. It was assumed that the vapor under the anti-slosh baffle forms a torus with the minor diameter equal to the baffle depth. This is a very conservative approach, since such a condition cannot exist physically. (The surface tension force will result in discrete bubbles.) However, it represents an upper limit for the vapor entrained under the baffle.

VAPOR VOLUME IN THE BULK OF LIQUID HYDROGEN FOR A CONTINUOUS VENTING SYSTEM, SATURN V/S-IV B STAGE

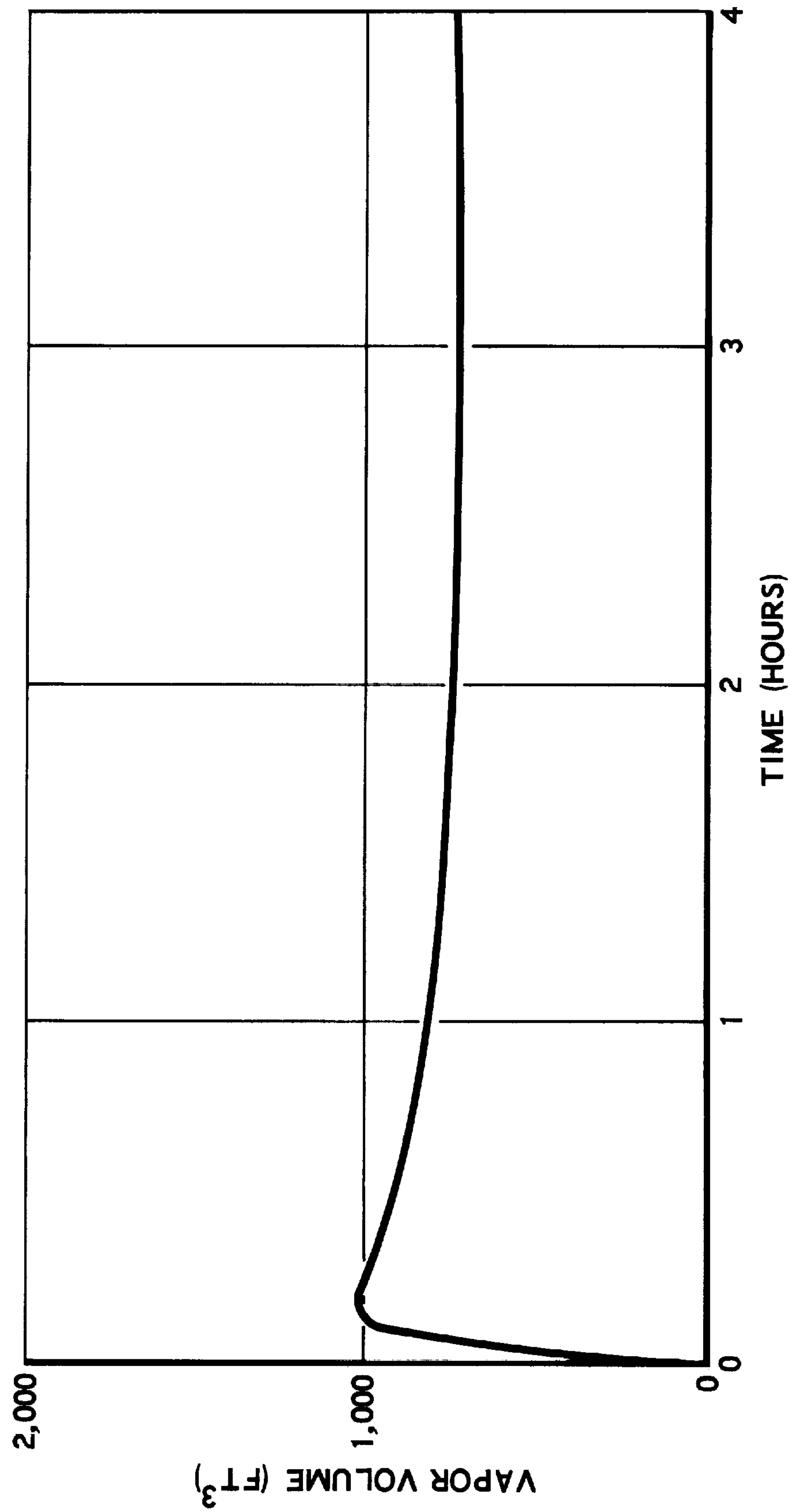


FIGURE 31

VAPOR VOLUME IN THE BULK OF LIQUID HYDROGEN FOR A CONTINUOUS VENTING SYSTEM, 203 EXPERIMENT

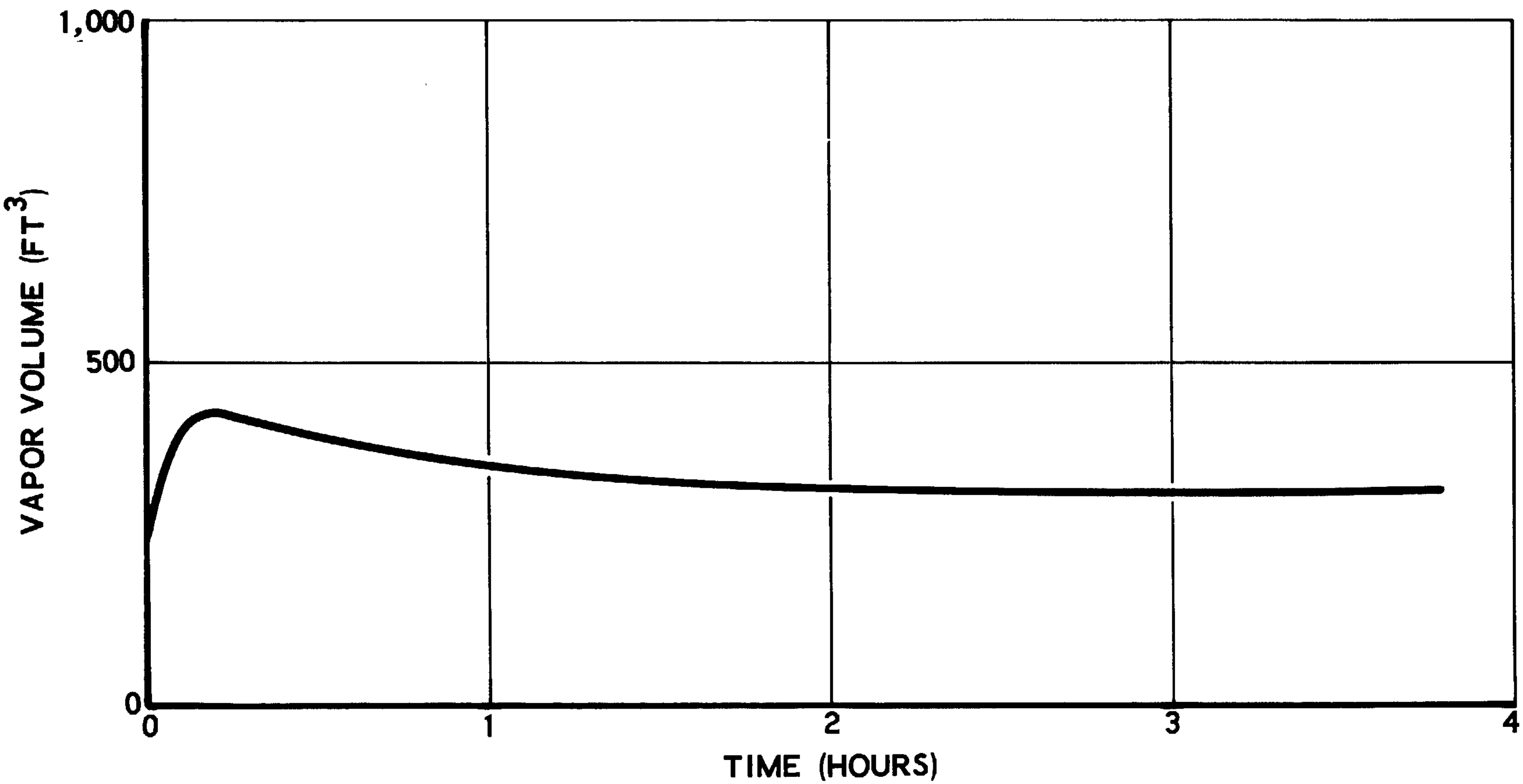


FIGURE 32

b. It was assumed that the vapor under the anti-slosh baffle consists of discrete bubbles equal in diameter to the baffle depth and spaced one foot apart. This probably is a realistic assumption.

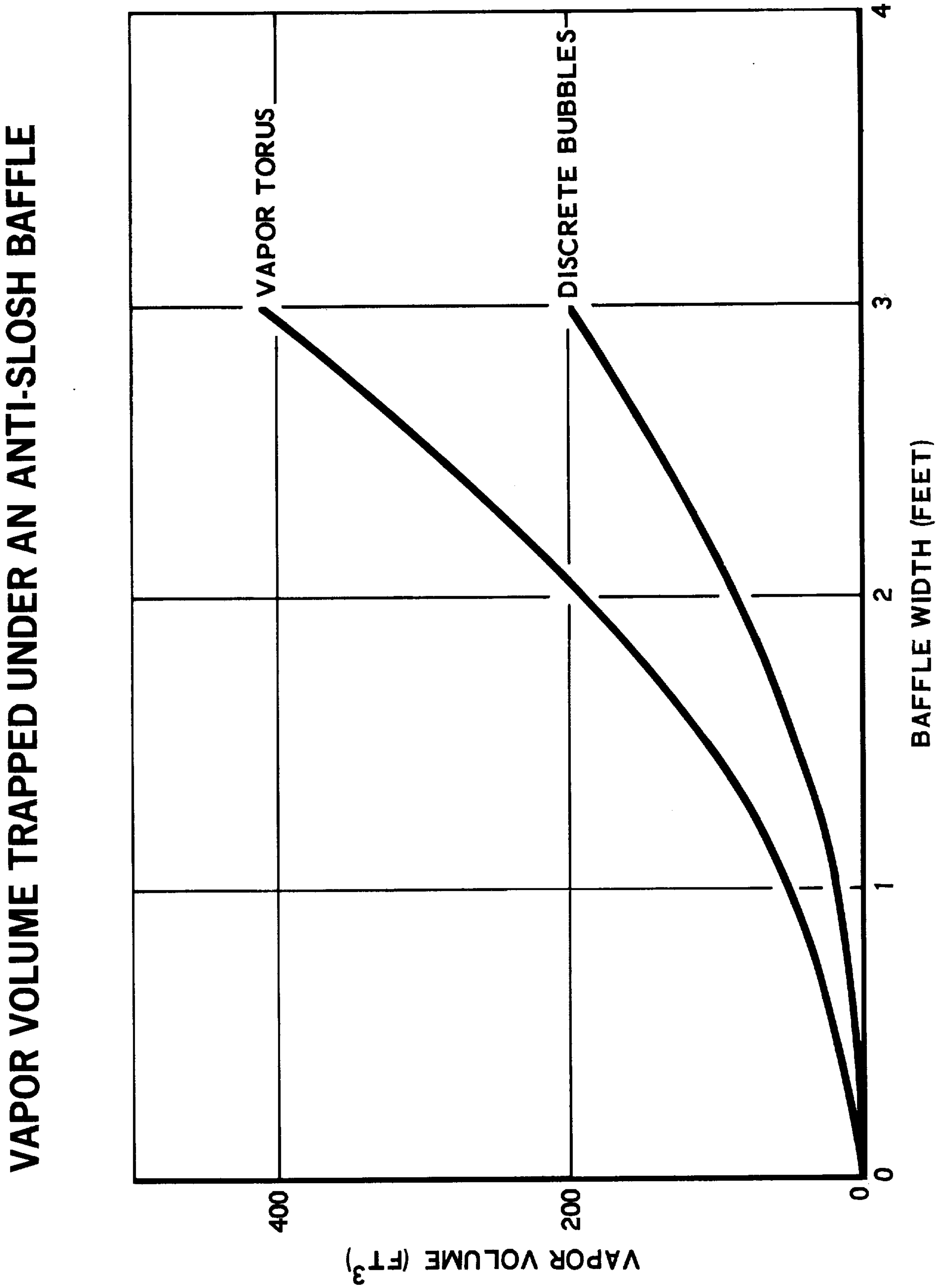
The vapor volume entrained under the anti-slosh baffle is given in Figure 33.

8. Design Considerations and Discussion

The vapor entrainment in the bulk of the liquid and the increase in the meniscus height in a low gravity field will not present any major problems in the continuous venting system design. However, the total liquid surface rise due to these effects should be considered where it affects some particular design problem. For instance, the location of the liquid deflector baffle depends on the liquid level location. This baffle should be located in the vapor space. The total liquid level rise due to the vapor entrainment and meniscus height is given in the table below. A 22-inch anti-slosh baffle was used in the calculations.

Cause of Liquid Level Rise	Liquid Level	Rise (Ft)
	Saturn V/S-IVB	Saturn IB/S-IVB-Experiment
Meniscus Height	1.5	1.5
Vapor in Boundary Layer	2.7	1.2
Vapor Trapped under the Anti-Slosh Baffle	0.4	0.4
Total	4.6	3.1

The approach used in the analysis was discussed quite extensively with M. M. Sutterlee of Lockheed Missiles and Space Company. His opinion was that the analysis is conservative and that the problem of vapor entrainment will probably be less severe than indicated by the analysis.



VAPOR VOLUME TRAPPED UNDER AN ANTI-SLOSH BAFFLE
VAPOR TORUS
DISCRETE BUBBLES
VAPOR VOLUME (FT^3)
0
200
400
BAFFLE WIDTH (FEET)
0
1
2
3
4

FIGURE 33